NREL Power System Research

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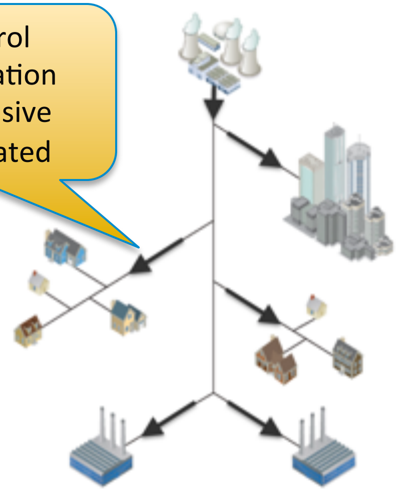
Evolution of the Grid

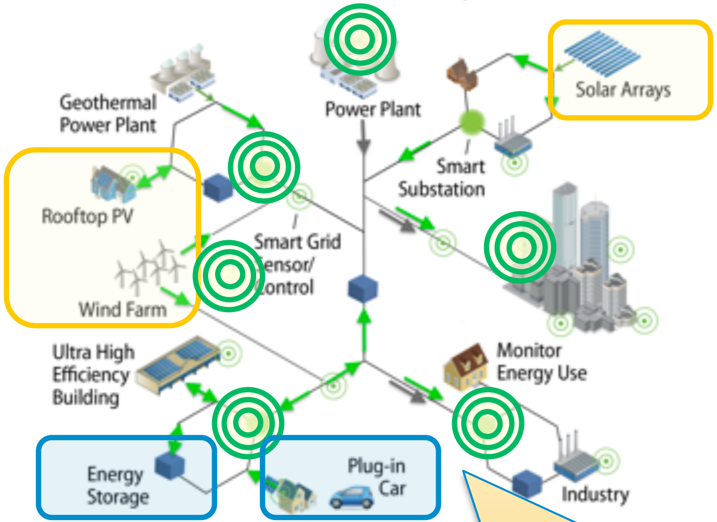
Energy Systems Integration

Current Power System

- Central Control
- Large Generation
- Carbon Intensive
- Highly Regulated



Future Power Systems



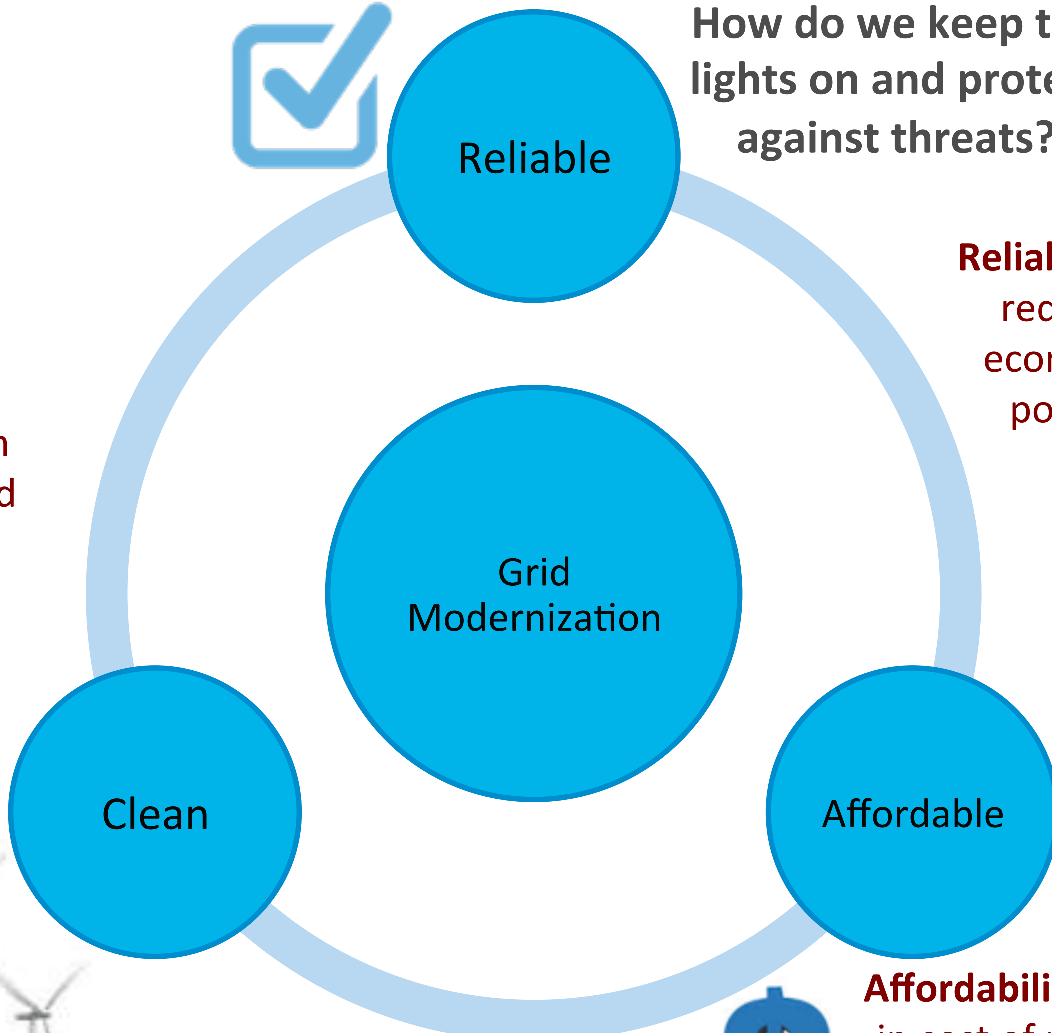
DRIVERS
- Increased variable gen
- More bi-directional flow at distribution level
- Increased number of smart/active devices
- Evolving institutional environment

New Challenges in a Modern Grid

- New energy technologies and services
- Increasing penetration of variable renewables in grid
- New communications and controls (e.g. Smart Grids)
- Electrification of transportation
- Integrating distributed energy storage
- Modern grid attributes: Reliable, Resilient, Secure, Affordable, Clean, Flexible, Innovative

Key Attributes of a Modernized Grid

Energy Systems Integration



How do we keep the lights on and protect against threats?

Reliability Goal: 10% reduction in the economic costs of power outages

Clean Goal: 50% cut in the costs of Distributed Energy Resources integration

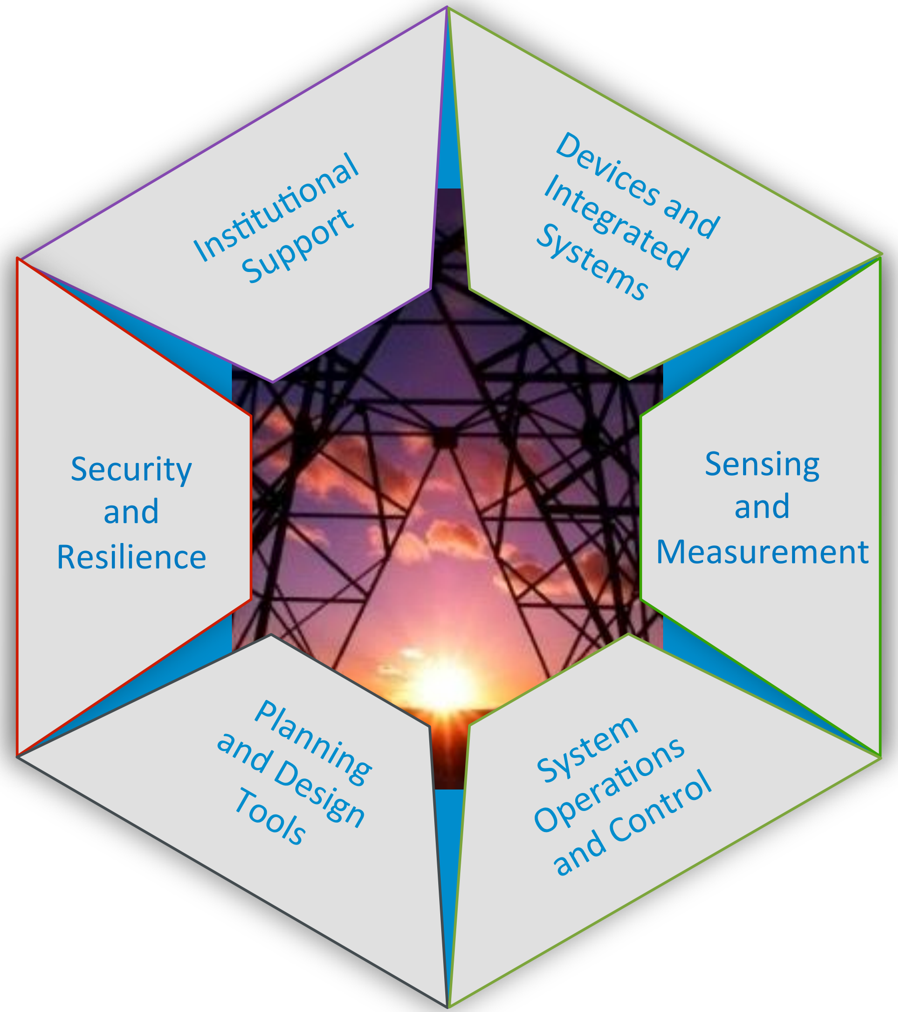
How do we reduce our environmental impact?

How do we keep costs reasonable for consumers?

Affordability Goal: 33% decrease in cost of reserve margins while maintaining reliability

Grid Modernization Foundational R&D Activities

Energy Systems Integration

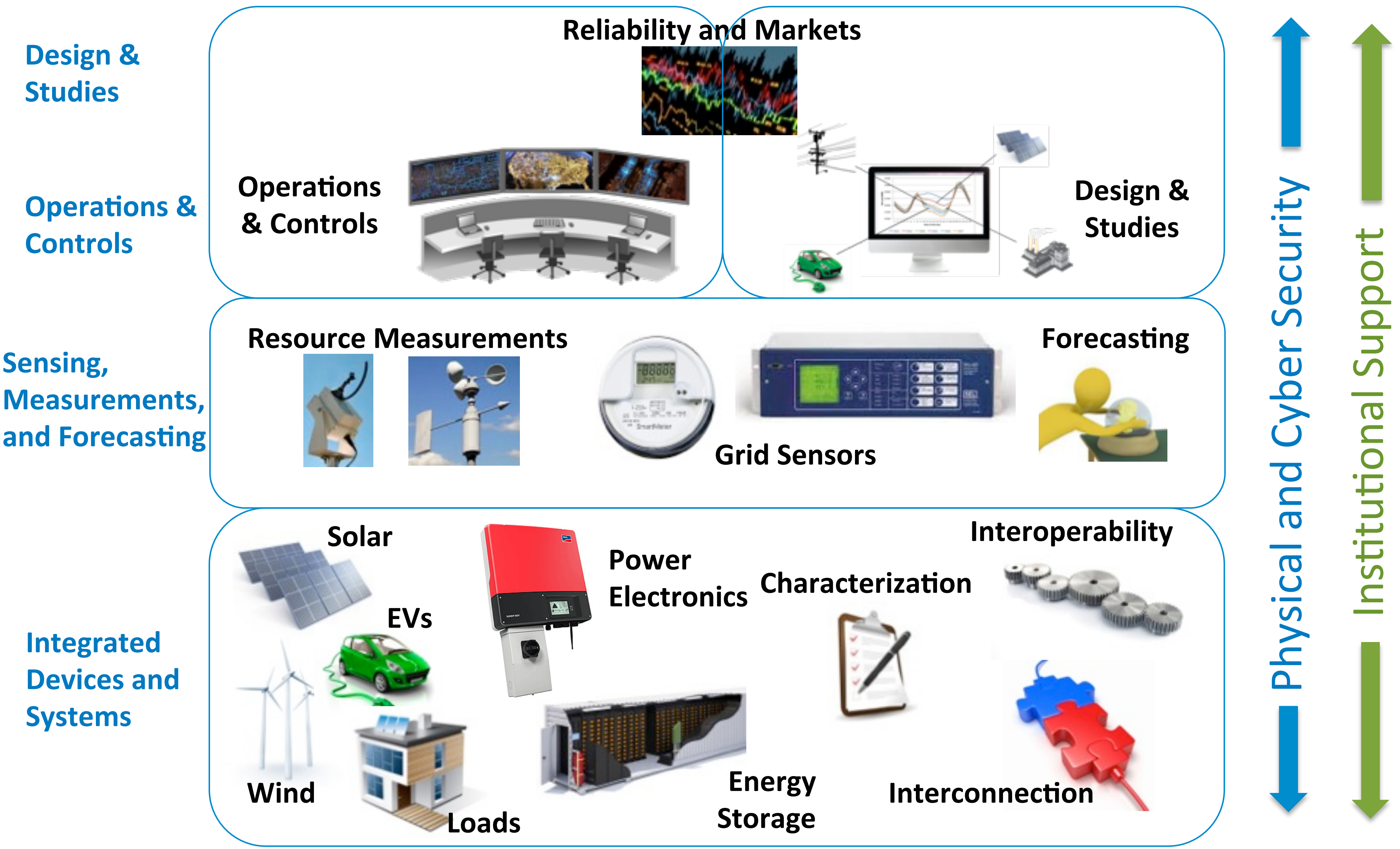


February 11, 2016

NREL Power Systems Research

NREL Provides Solutions

Energy Systems Integration



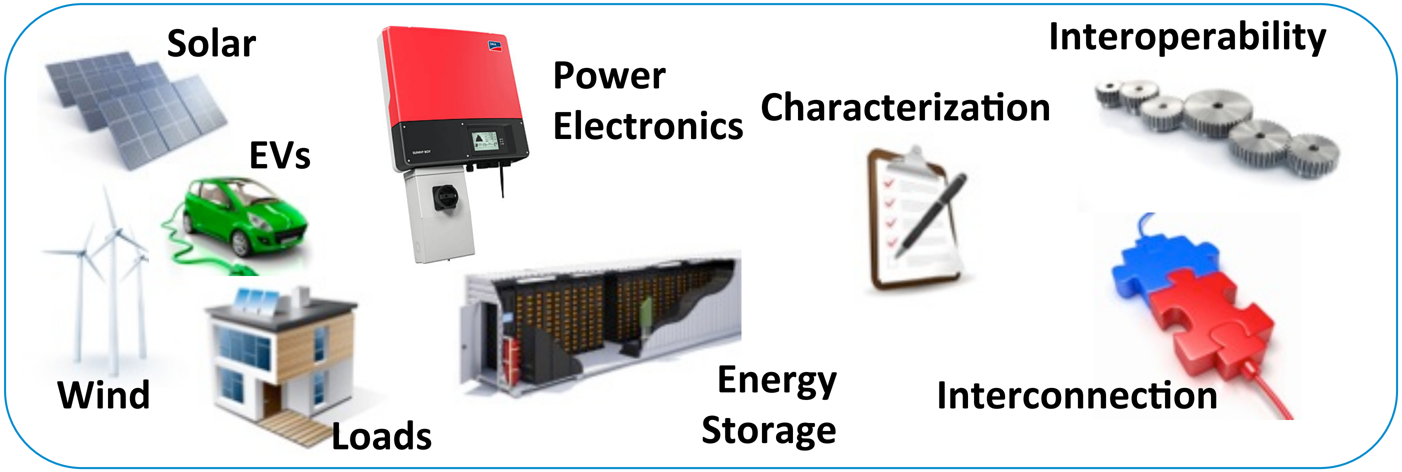
PSEC – Power Technologies and Testing

Energy Systems Integration

Core Expertise:

- Development and Testing of new Power Electronics Inverters/Converters
- Power Hardware-in-the Loop Development and Testing
- System Prototyping and Testing (High Pen DER circuits and Microgrids)
- Modeling, Simulation and Testing of Energy Storage Systems

Integrated Devices and Systems



Energy Systems Integration Facility (ESIF)

Energy Systems Integration

http://www.nrel.gov/esif

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

Unique Capabilities

- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation and loads
- Flexible interconnection points for electricity, thermal, and fuels
- Medium voltage (15kV) microgrid test bed
- Virtual utility operations center and visualization rooms
- Smart grid testing lab for advanced communications and control
- Interconnectivity to external field sites for data feeds and model validation
- Petascale HPC and data mgmt system in showcase energy efficient data center
- MW-scale Power hardware-in-the-loop (PHIL) simulation capability to test grid scenarios with high penetrations of clean energy technologies

Shortening the time between innovation and practice

ESIF Laboratories

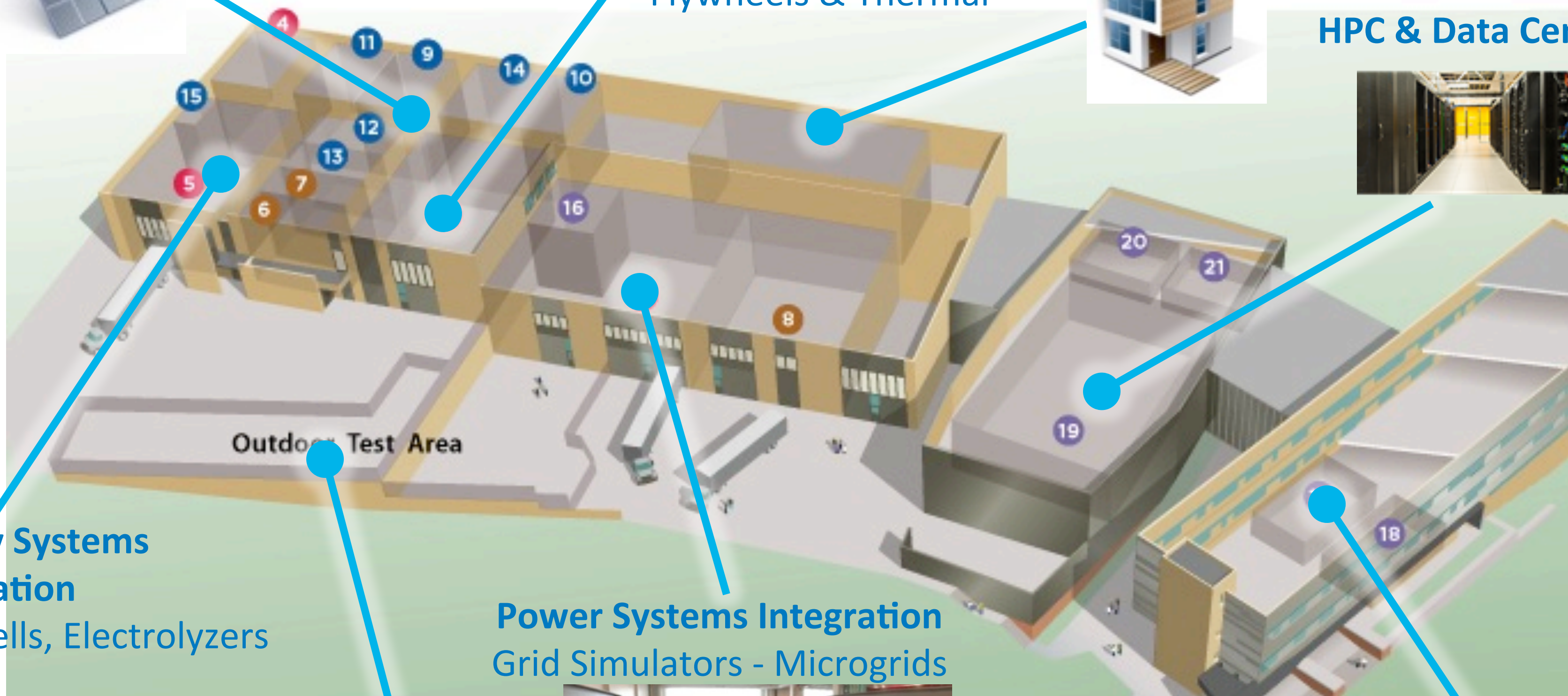
Energy Systems Integration

Rooftop PV

Energy Storage -
Residential, Community & Grid Battery Storage, Flywheels & Thermal

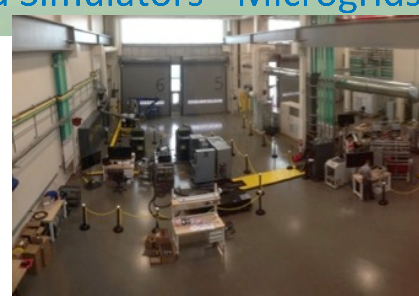
Smart buildings & controllable loads

HPC & Data Center



Energy Systems Integration
Fuel Cells, Electrolyzers

Power Systems Integration
Grid Simulators - Microgrids



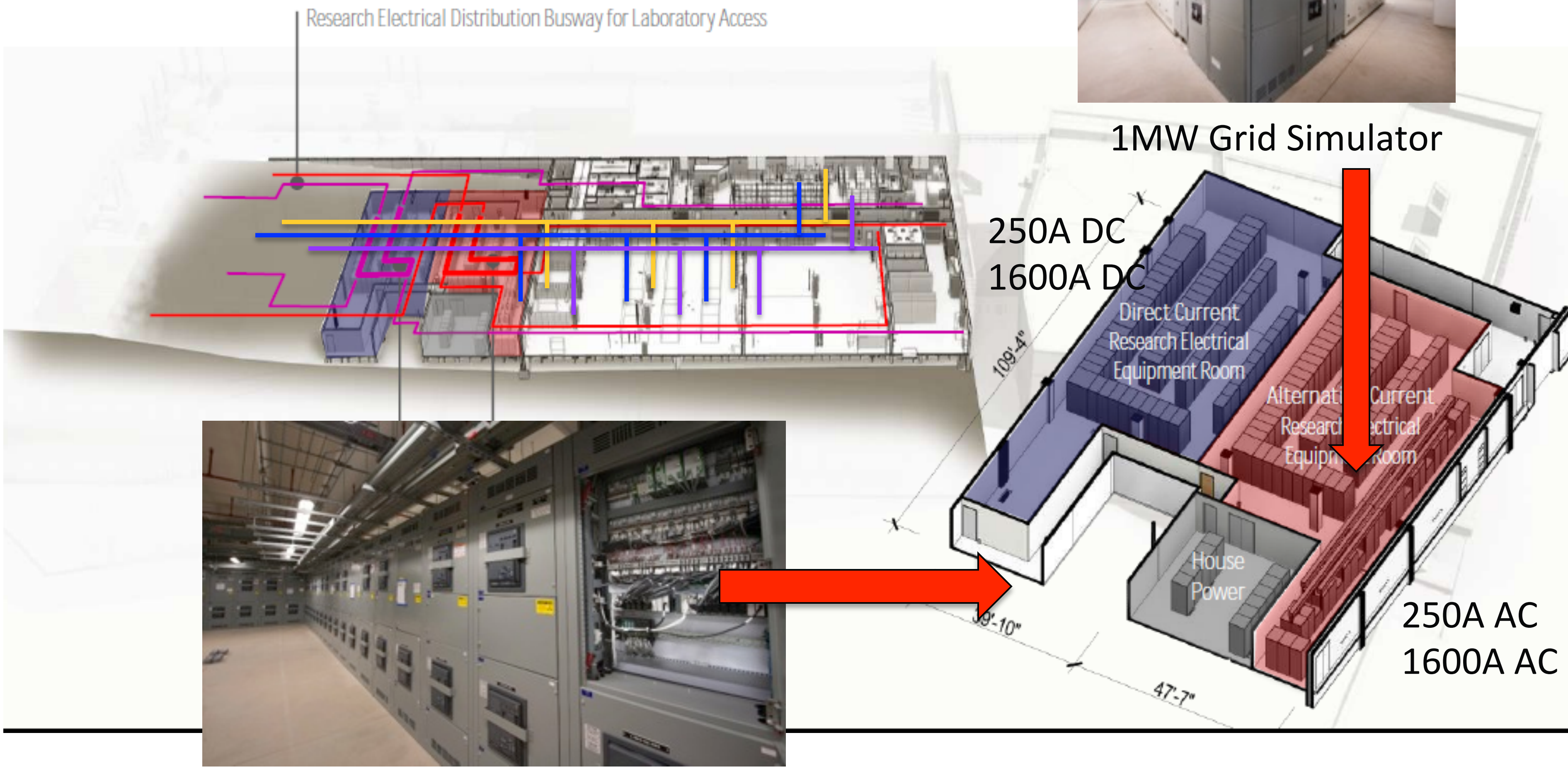
Outdoor Test Areas
EVs, Power Transformers

Advanced Distribution Management Systems

ESIF Research Infrastructure

Energy Systems Integration

- Research Electrical Distribution Bus – REDB (AC 3ph, 600V, 1200A and DC +/-500V, 1200A)
- Thermal Distribution Bus
- Fuel Distribution Bus
- Supervisory Control and Data Acquisition (SCADA)



Large-Scale Grid, PV, and Load Simulators

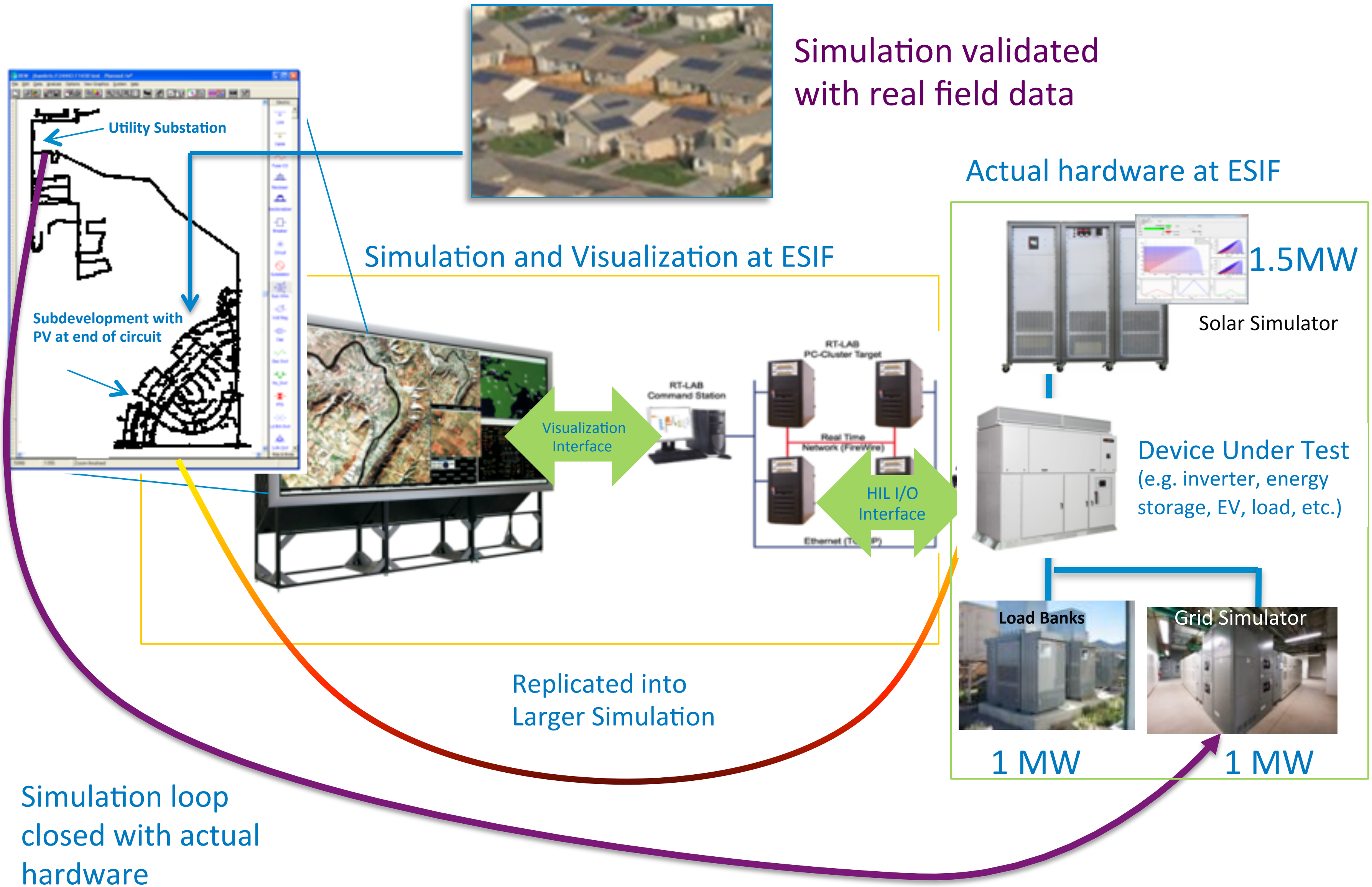

1MW Grid Simulator


1MW RLC Load Bank


1.5MW PV Array Simulator

Power Hardware-in-the-Loop: Connecting Experiments to Simulations

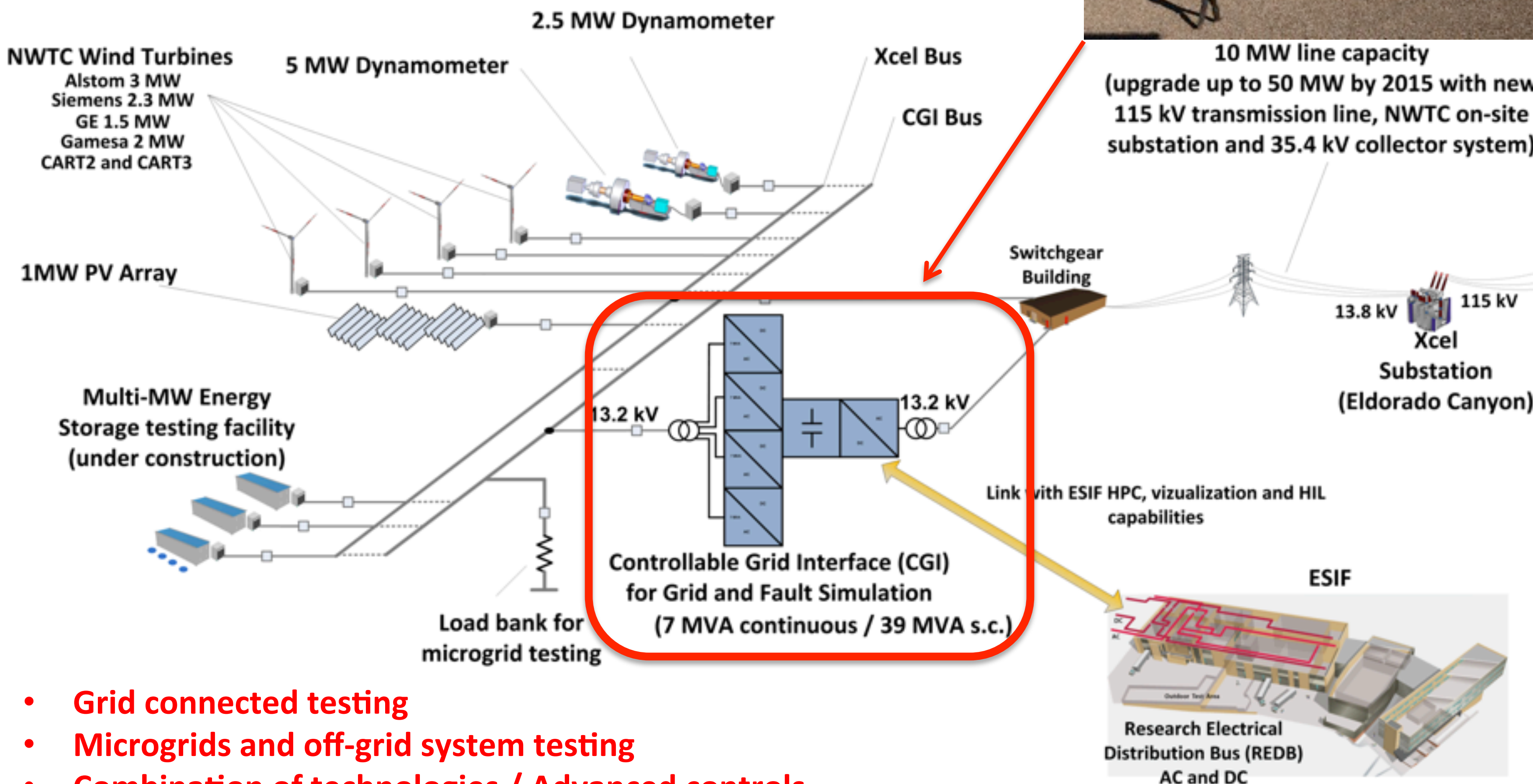
Energy Systems Integration



NREL – ESI at NWTC

Energy Systems Integration

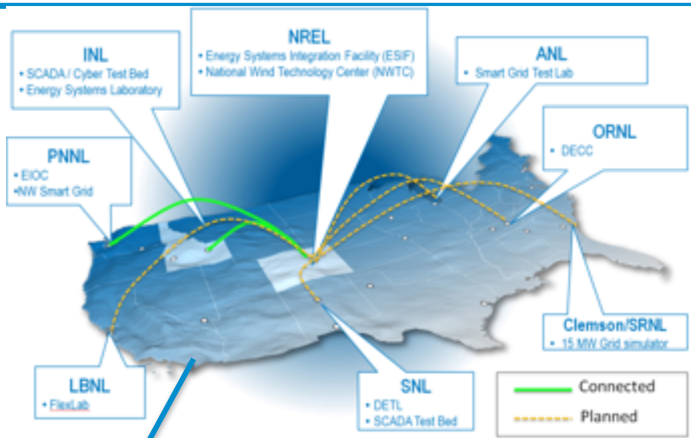
- Highly flexible and configurable controllable grid interface (CGI) for system level multi-MW testing/ demonstration platform
- Switchgear upgrade to connect field turbines and energy storage pads completed



- Grid connected testing
- Microgrids and off-grid system testing
- Combination of technologies / Advanced controls

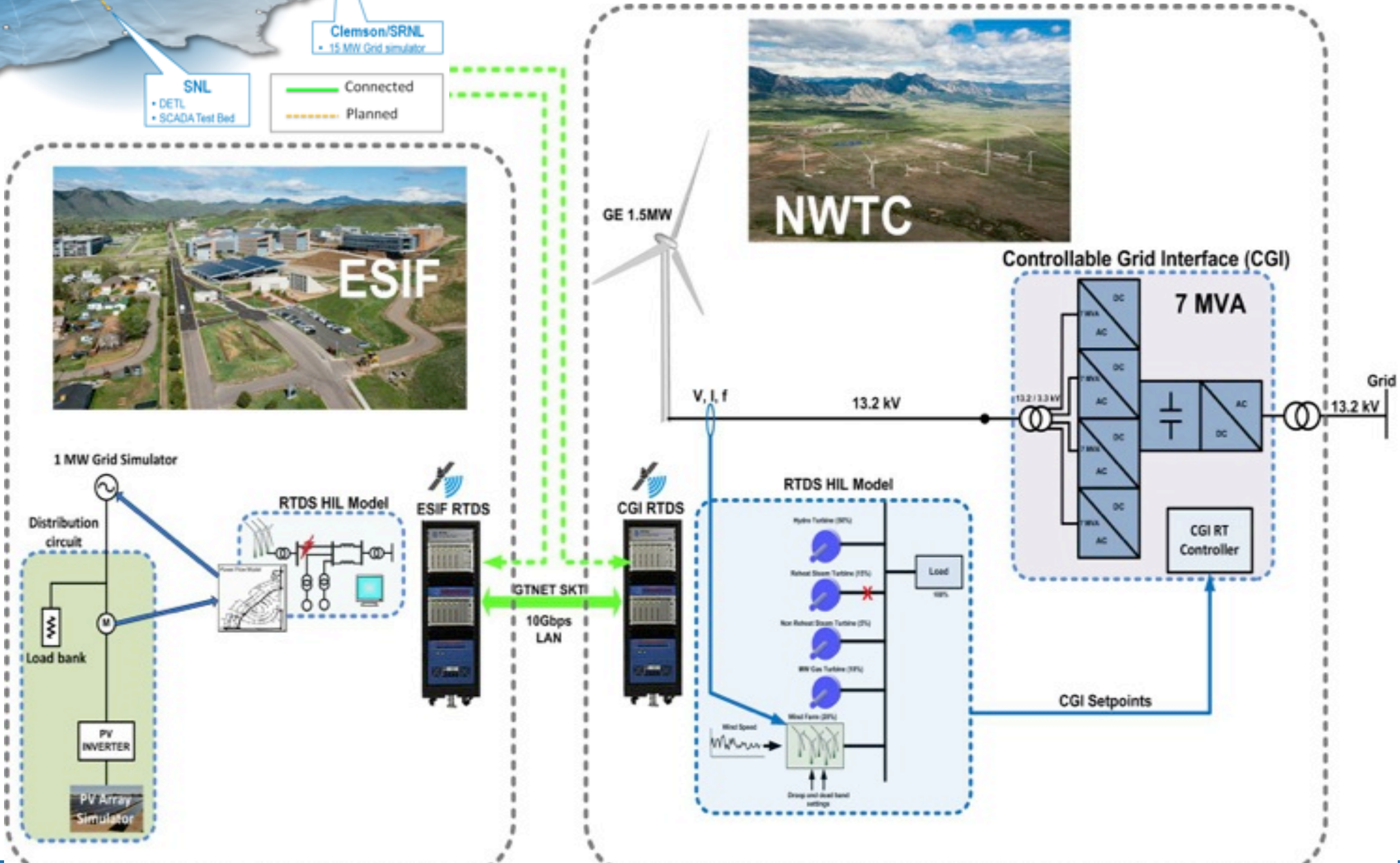
Remote Hardware in the Loop Capability

Energy Systems Integration



Connection to Industry partner SDG&E

IMPACT
First of a kind remote HIL experiments increase testing capability without large investments in physical equipment at multiple sites



NREL + SolarCity + Hawaii Electric – PV Integration

TECHNOLOGY ADDRESSED

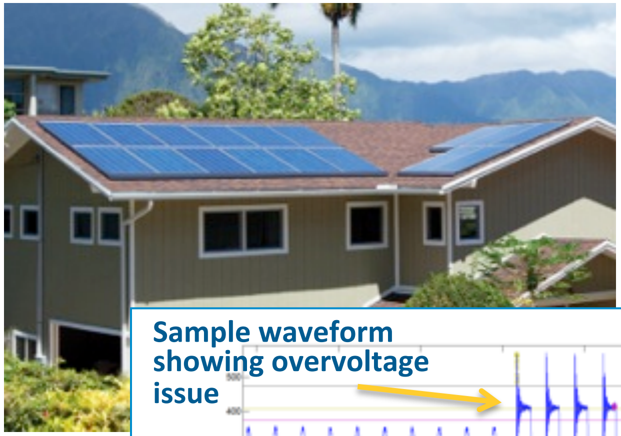
Interconnection challenges when connecting distributed PV at high penetration into the electrical distribution grid such as in Hawaii.

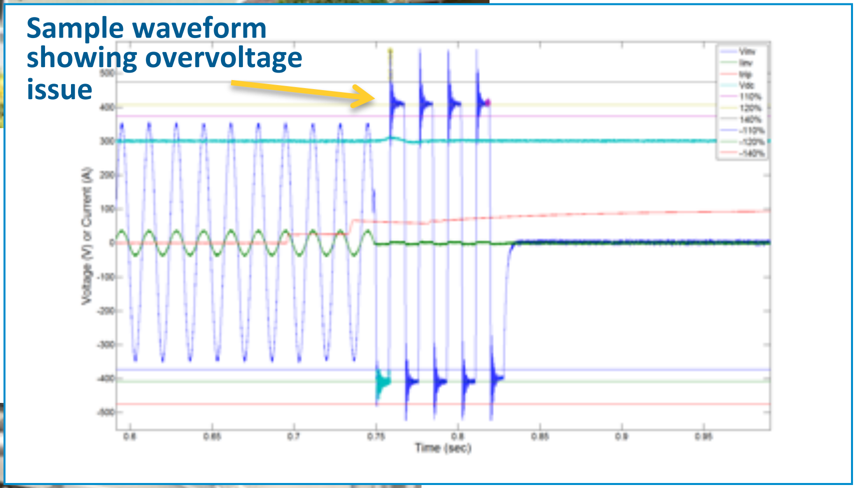
R&D STRATEGY

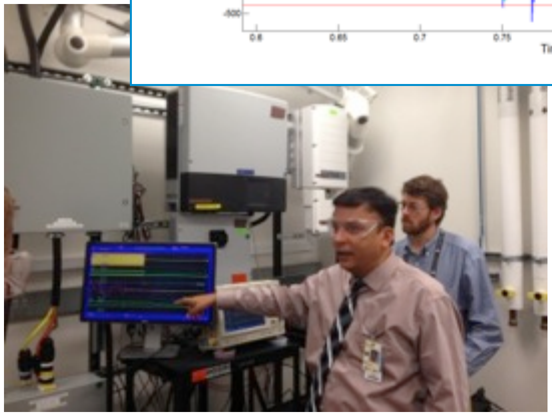
Test solar inverters from various manufacturers for their ability to mitigate transient overvoltage impacts

IMPACT

HECO filed with the PUC to modify their interconnection policies to allow siting of PV systems with advanced inverters on neighborhood distribution circuits up to 250% of minimum daytime load (MDL).





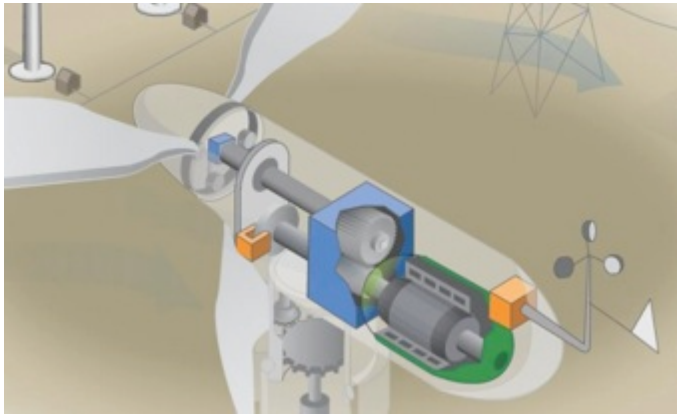


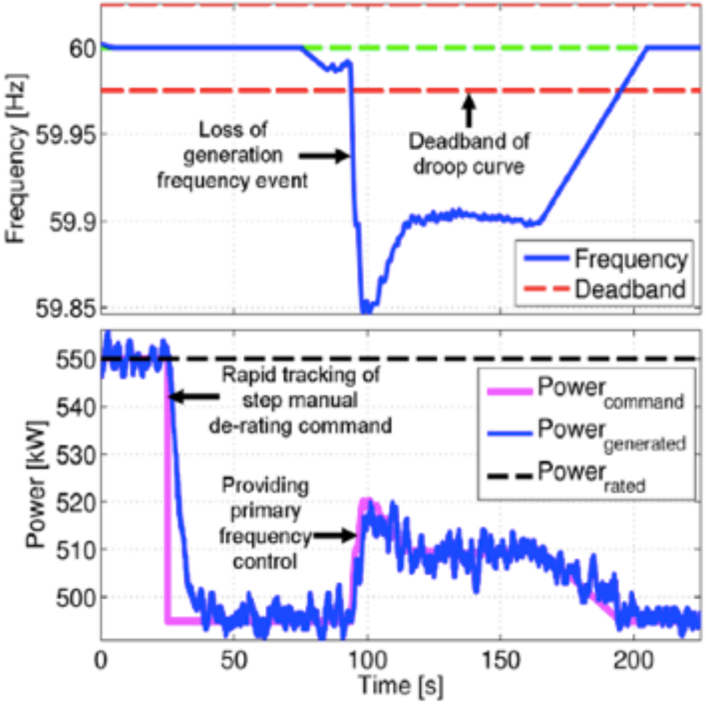
Active Power Control from Variable Gen

Energy Systems Integration

- **Understanding how Variable Generation (Wind and Solar) can provide primary and secondary reserves.**

- **Inertial control, Primary Frequency Control (PFC), and Automatic Generation Control (AGC) from Wind and Solar is feasible with negligible impacts on loading**



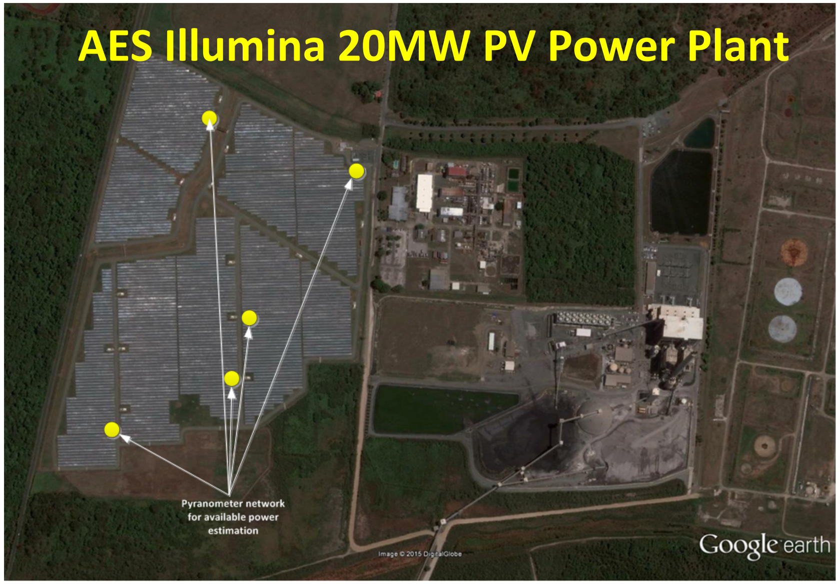


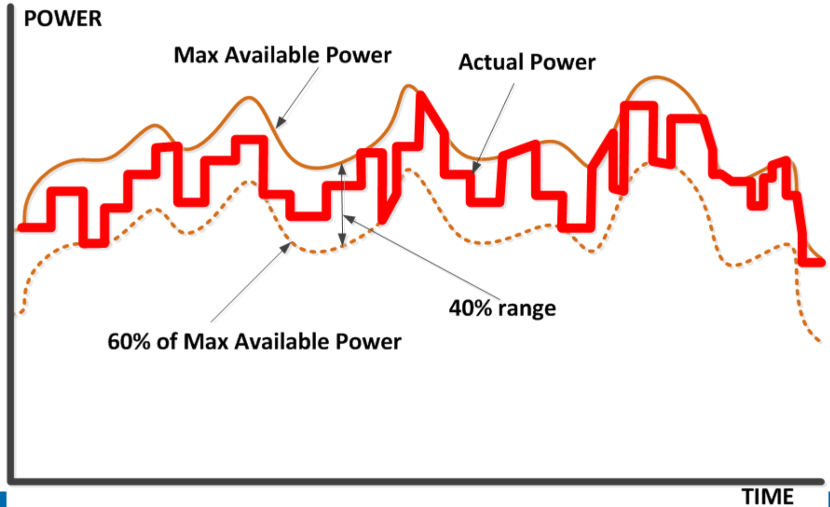
NREL + Puerto Rico Utility

Energy Systems Integration

Demonstrate PV can provide grid ancillary services for island

- **Project Team: NREL, AES, GPTech, and PREPA**
- **Plant participation in Automatic Generation Control (AGC)**
  - Follow PREPA AGC signal within 40% of available power
- **Plant providing frequency droop response**
  - Both up and down-regulation
  - 5% and 3% symmetric droop
- **Fast Frequency Response (FFR) tests**
  - Test plant's ability to deploy all reserve within 500 ms
  - Three new controls were implemented and validated





Impact
First of a kind real-world experiment using PV systems to maintain large grid stability

Sensing, Measurements, and Forecasting

Resource Measurements

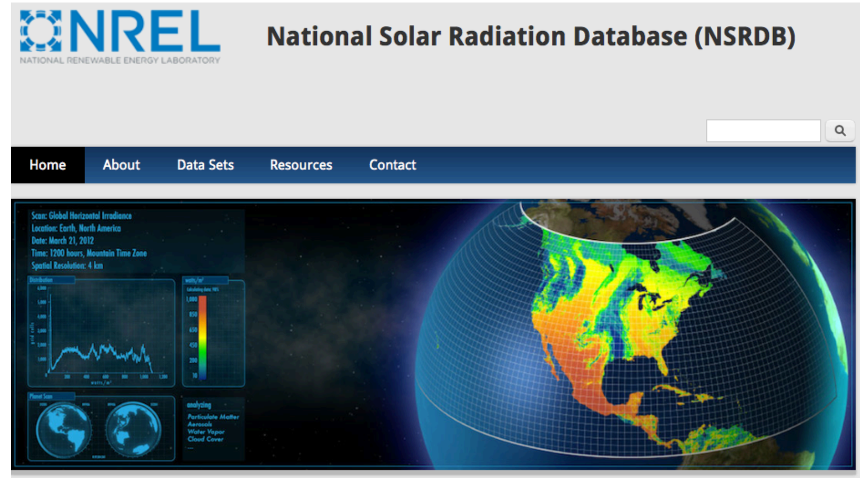
Grid Sensors

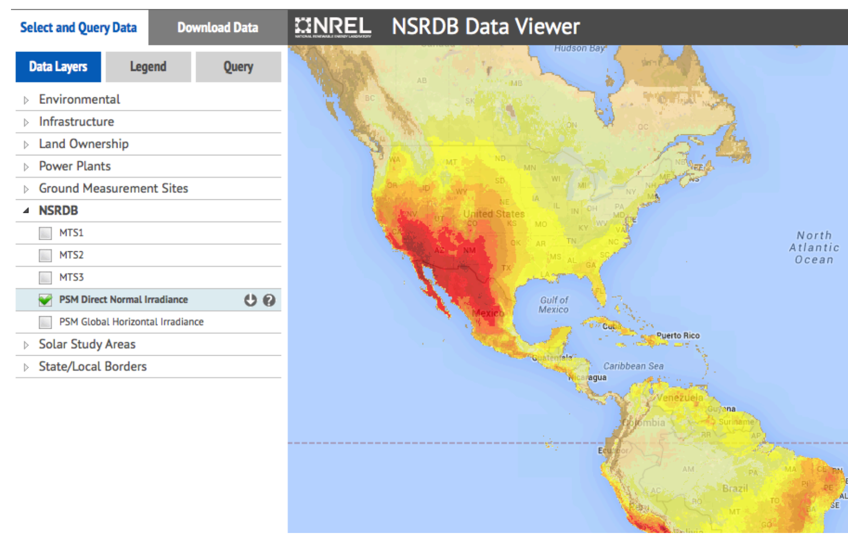
Forecasting

Updated NSRDB – New level of solar resource data

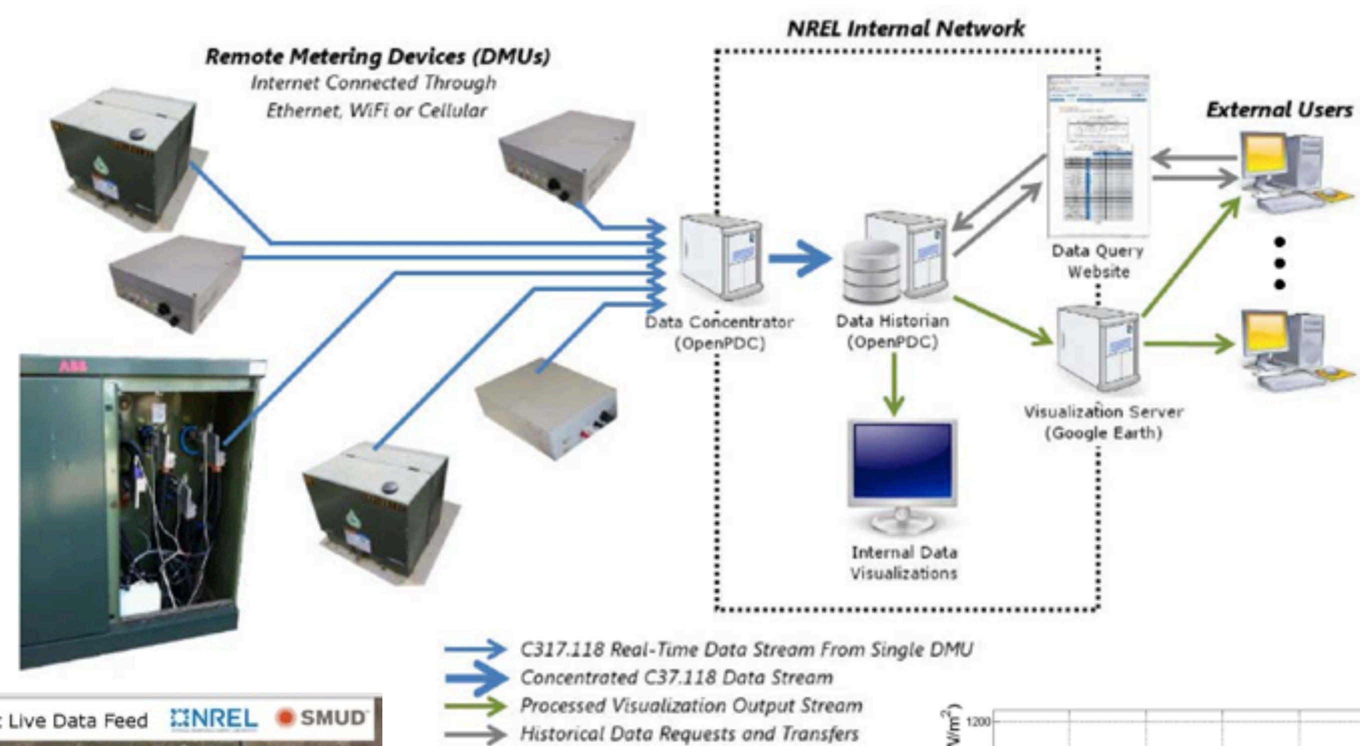
- National Solar Radiation Data Base (NSRDB) (http://nsrdb.nrel.gov)
- High-resolution satellite based solar resource datasets from 1998-2014 using advanced methods
- Real time satellite based resource data for grid integration

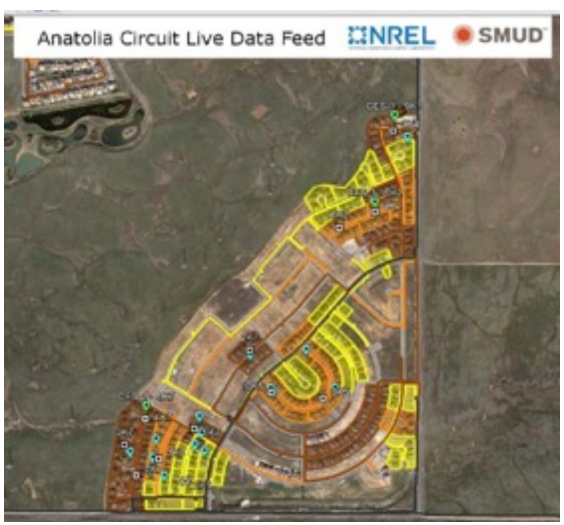
Impact: Unprecedented Level of publicly available information on solar resource data

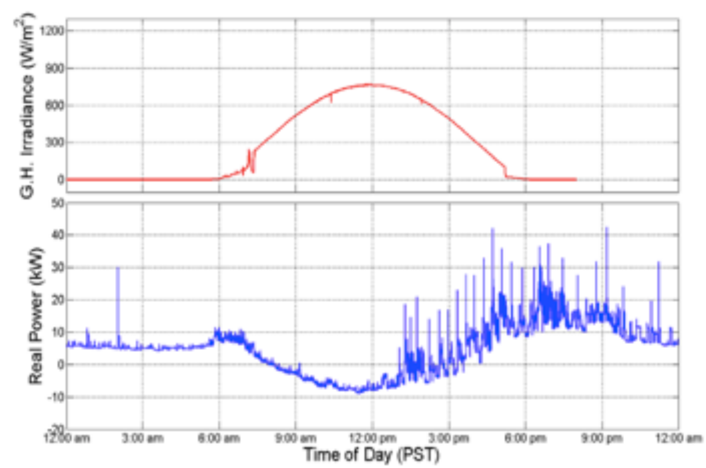




DMUs for Renewable Integration



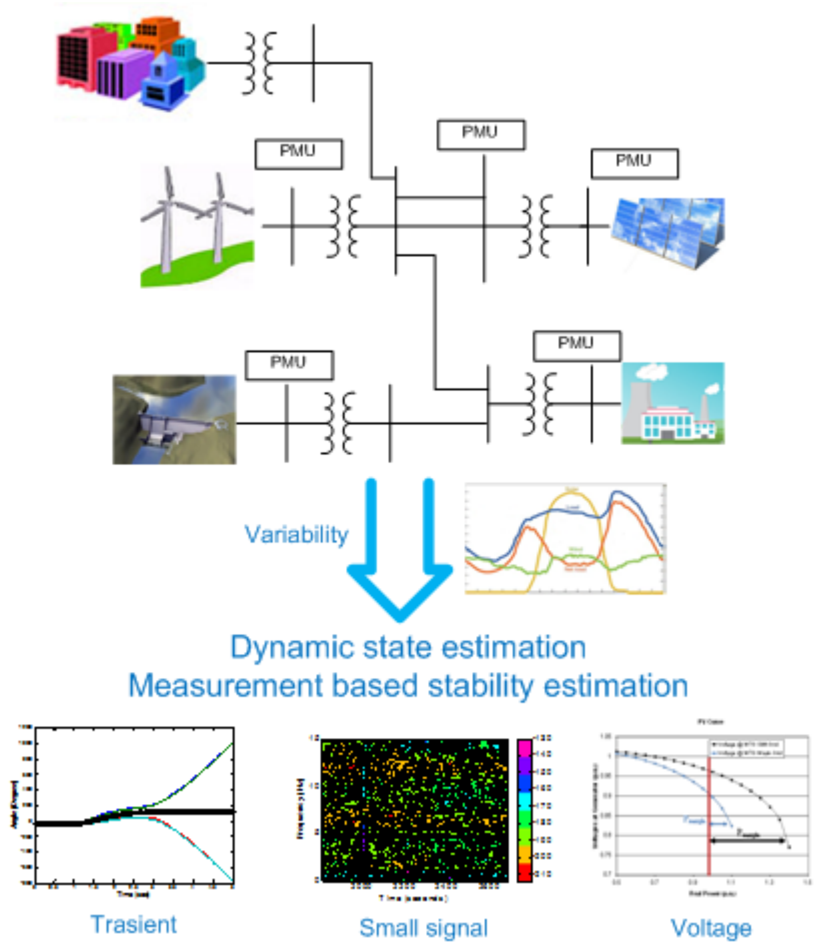




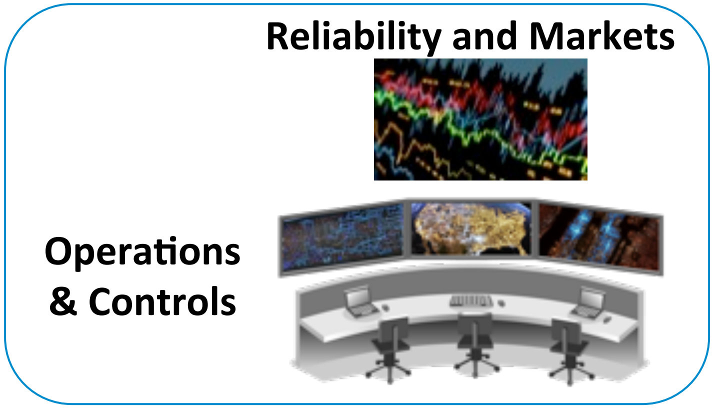
PMUs for Renewable Integration

- **PMU provides millisecond level scan of the power system that can be used for**
  - Dynamic state estimation
    - Quasi-steady state estimation
    - Trajectory prediction
  - Measurement-based stability estimation
    - Transient stability
    - Small signal stability
    - Voltage stability
    - Frequency stability
  - Flexible and fast acting control of power system

- **Investigating PMU-based control algorithms to improve the operation of renewable energy from the perspectives of WAMPAC (Wide Area Monitoring Protection and control) utilizing availability of power electronics**



PSEC – Operations and Controls

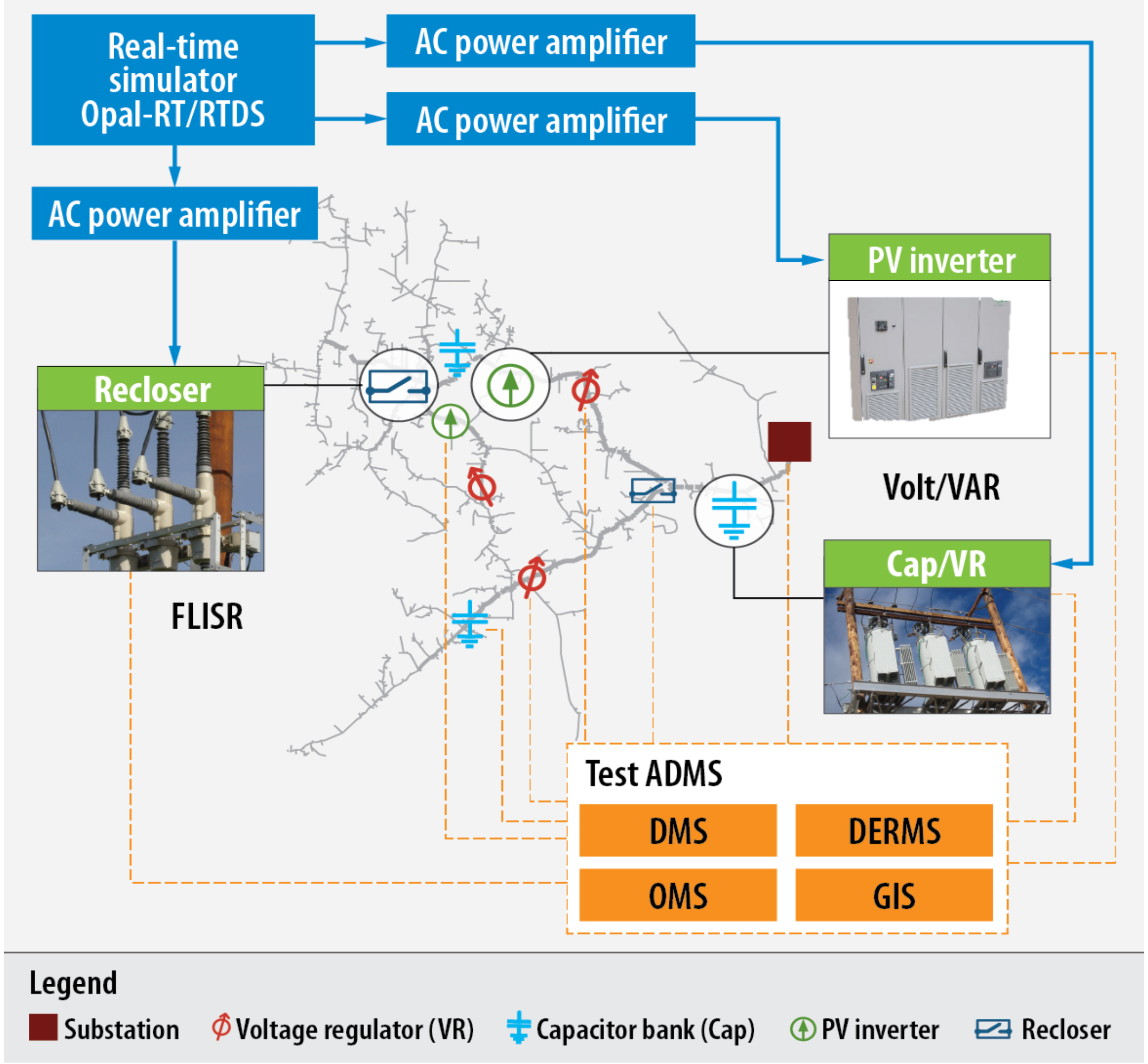


Operations & Controls

NREL ADMS Testbed

Energy Systems Integration

- Establish a **national, vendor-neutral** Advanced Distribution Management System (ADMS) testbed to **accelerate industry development and adoption of Advanced Distribution Management System (ADMS) capabilities** for the next decade and beyond.
- Enable utility partners, vendors, and researchers to evaluate existing and future ADMS use cases



Team Partners: NREL, PNNL, ANL, EPRI, GE Grid Solutions, Schnider Electric and Opal-RT

Functional Specifications

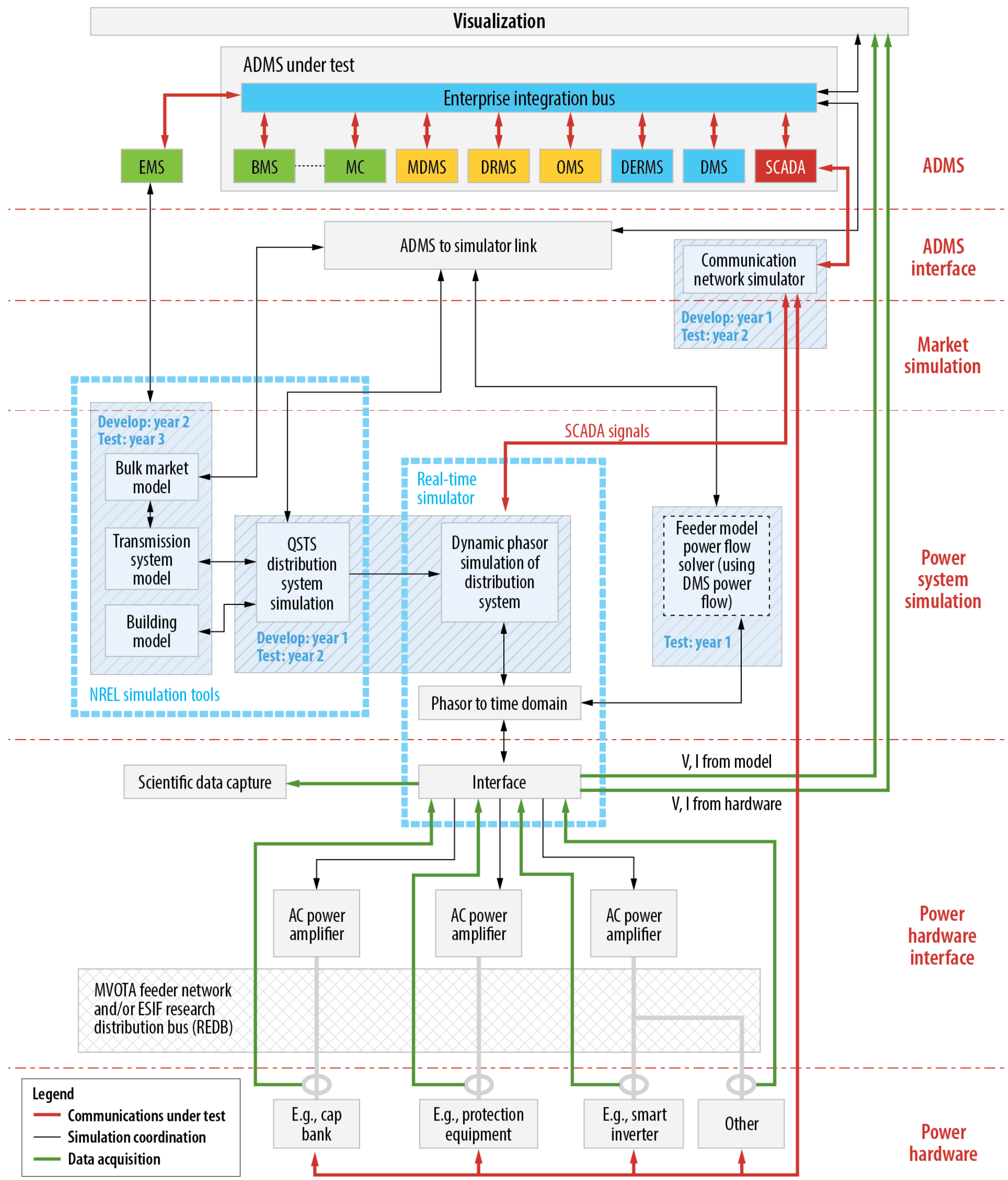
Energy Systems Integration

- ADMS
- A supervisory control and data acquisition (SCADA) interface, and
- Other utility management systems

Year 1: Internal Power Flow Solver implementation

Year 2: multi-timescale software model evaluation

Year 3: Integrated application demonstration



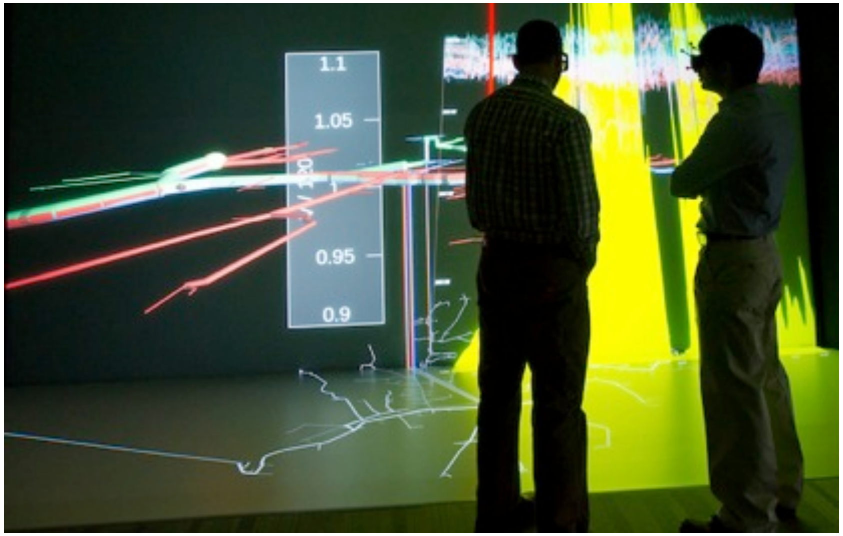
Duke Energy and Alstom DMS Volt/VAR testing

Energy Systems Integration

TECHNOLOGY ADDRESSED
Understand impacts of smart inverters on distribution systems and advanced distribution management systems

R&D STRATEGY
NREL is collaborating with Alstom Grid to implement a comprehensive modeling, analysis, visualization and hardware study using a representation of Duke Energy's utility feeder.

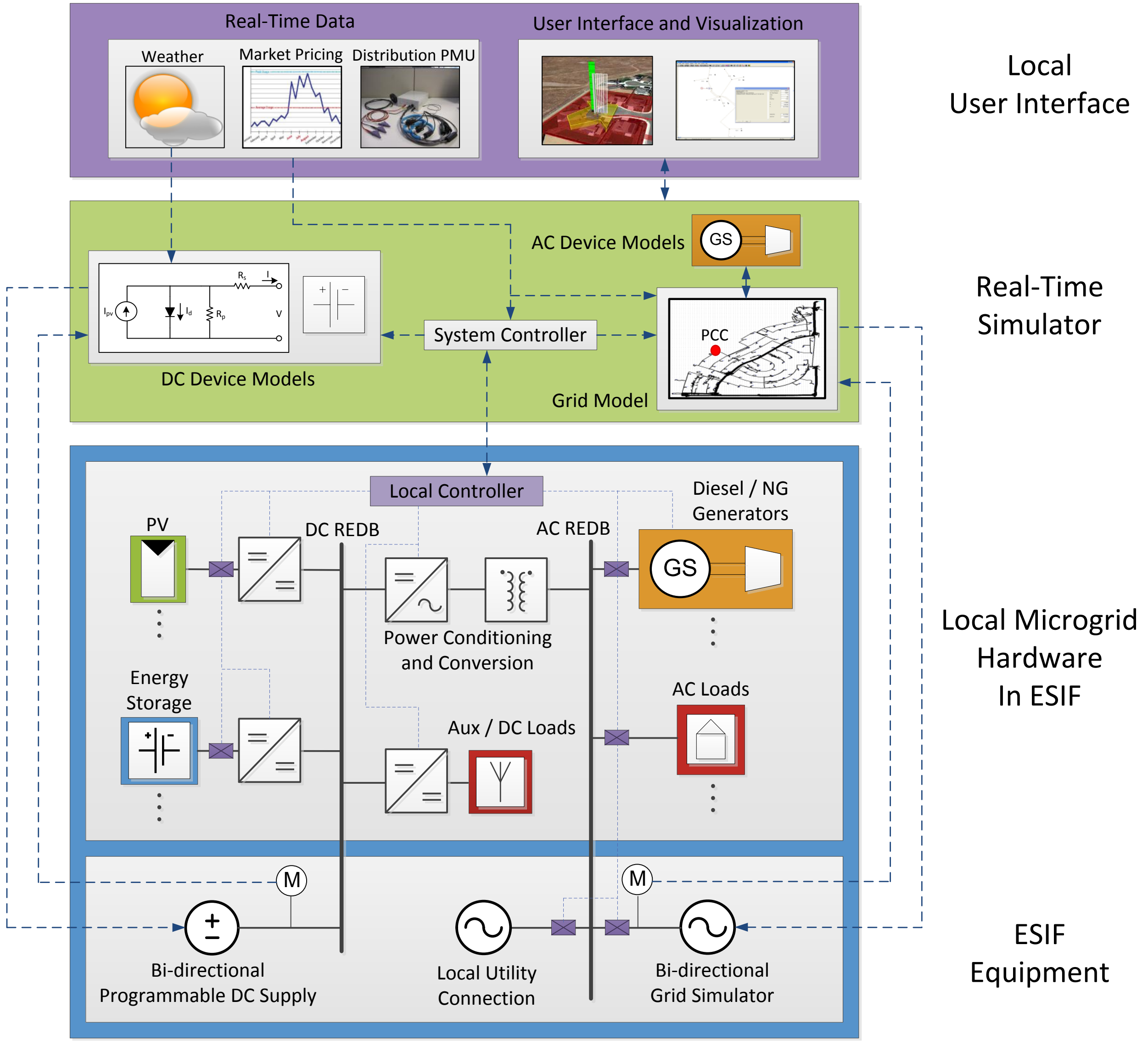
IMPACT
Enable greater adoption of smart inverters at utilities by addressing the challenges of integrating them with GIS, DMS, OMS and SCADA systems.



System-level Evaluation of Microgrid Controller

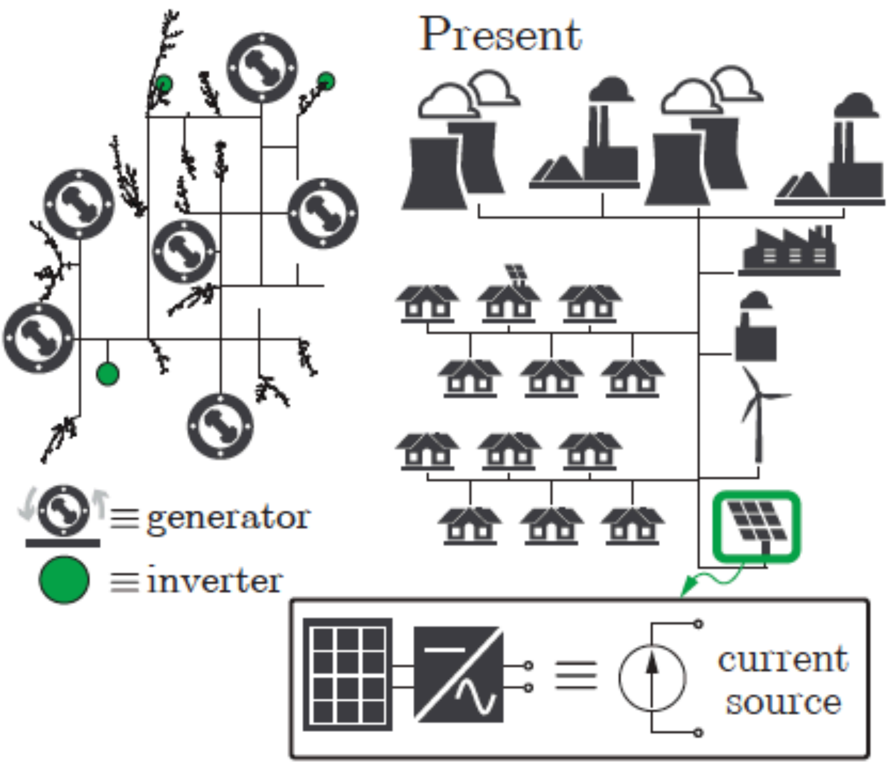
Energy Systems Integration

- Evaluation of microgrid controller using hardware at-scale with simulated power systems via power hardware-in-the-loop (PHIL) or controller hardware-in-the-loop (CHIL)
- MW-scale PHIL
- **RTDS and Opal-RT**

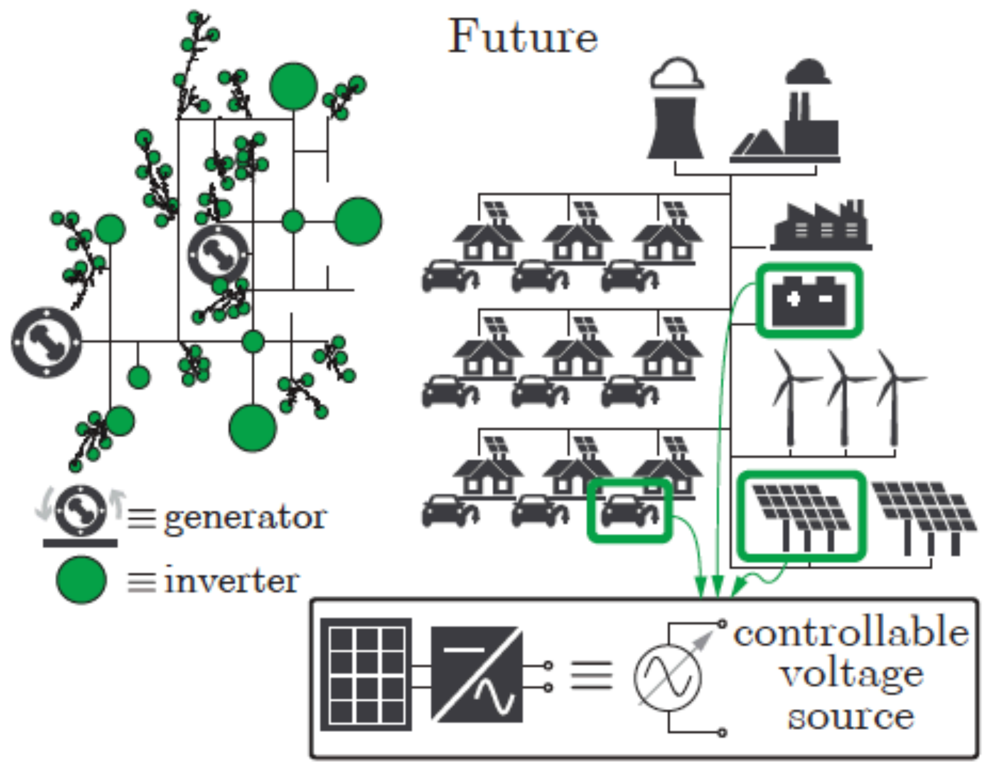


Developing Decentralized Controls

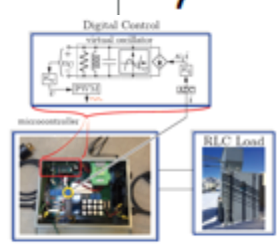
Energy Systems Integration



From grid-following controls



To next-generation grid-forming controls



PSEC – Design and Studies

Energy Systems Integration

Design & Studies

Distribution Planning Studies

Energy Systems Integration

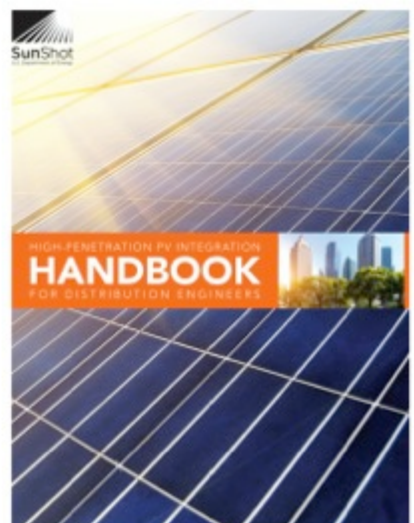
CORE EXPERTISE

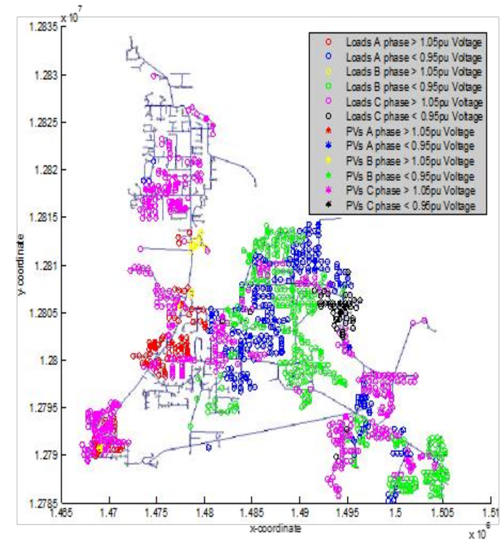
- Deep experience with analysis & integration of distributed energy resources (DERs): Solar, Wind, electric vehicles, buildings, etc.
- Blending commercial analysis packages (e.g. CyME, Synergi, DEW, Windmil) with open source and NREL developed tools.
- Lead: On The Path for SunShot-Distribution
- Statistical selection of typical feeders
- Past and existing projects with: Duke Energy, SCE, So Cal Gas, SDG&E, PG&E, SMUD, APS, HECO, National Grid, Xcel Energy, Pepco, ConEd, EPRI, CPUC, et al.

KEY APPLICATION:

Southern California Edison (SCE) High Penetration Solar PV Integration Project

NREL staff partnered with SCE to install 500 MW of utility-scale distribution-connected PV and to develop new best practices for utility planning engineers and developing methods to mitigate impacts using advanced inverters





Dev. Of New PV Interconnection Screens

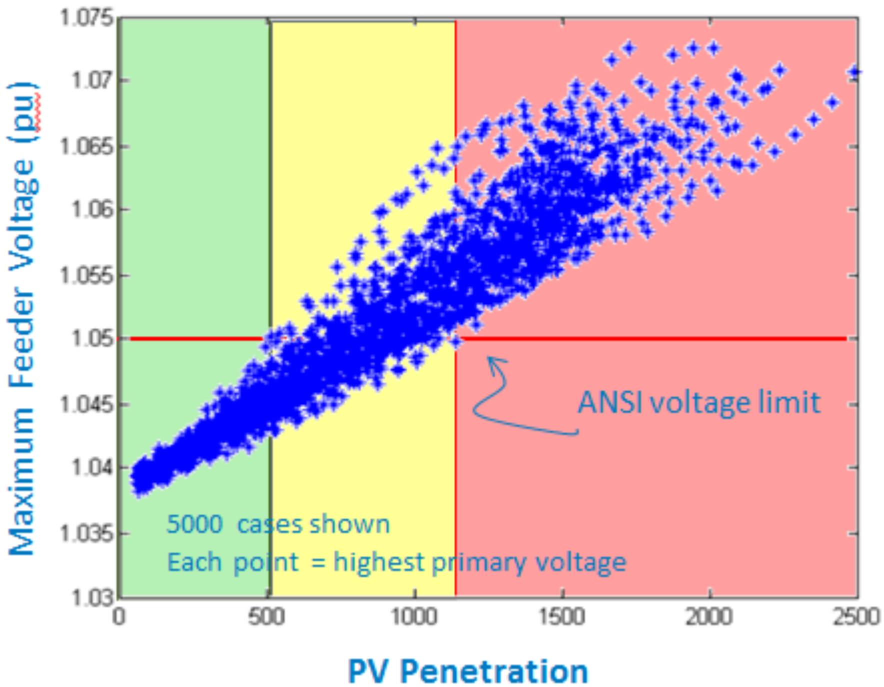
Energy Systems Integration

Project Overview:

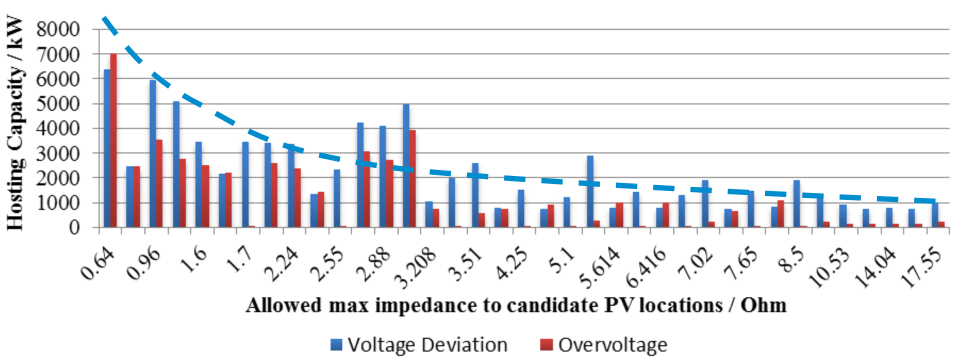
- Teamed with EPRI, SNL, PG&E, SCE, SDG&E, Pepco, and Xcel to develop new technical PV interconnection screens for fast track PV interconnection process
- Determined the hosting capacity of 30+ representative circuit overall
- Investigated the sensitivity of hosting capacity to simply implemented screens (e.g. distance to substation)

Project Details:

- Capabilities – detailed distribution modeling, model validation, hosting capacity determination, development of software tools
- Engagement – EPRI, SNL, CPUS, PG&E, SCE, SDG&E, Pepco, Xcel
- Tools – OpenDSS, EPRI's DPV tool, in-house developed hosting capacity tool
- Data – utility circuit models, utility SCADA data, stochastic hosting capacity modeling outputs

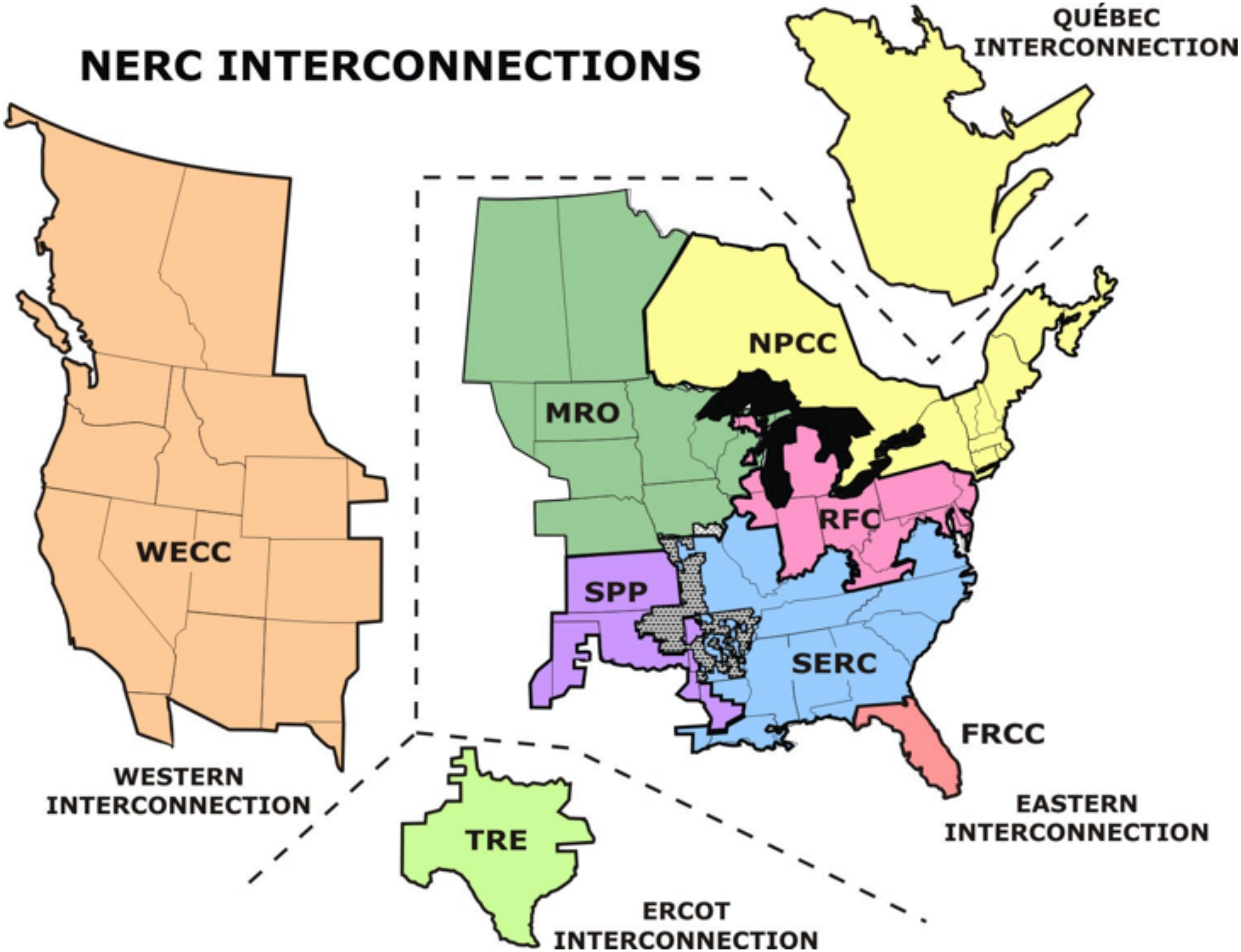


Example of Monte Carlo-Based Hosting Capacity Study Results



PV Screening Determination Based on Model Outputs

Bulk-Power Interconnections



Integrated Assessment

Energy Systems Integration

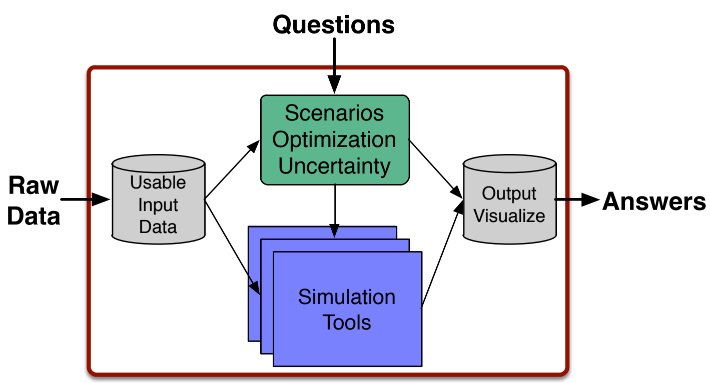
CORE EXPERTISE

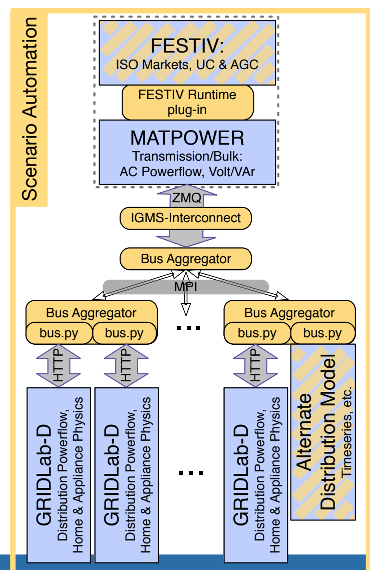
- Multi-perspective studies using separate tools across time and spatial scales
- Combined transmission-distribution simulation for DER impacts on system-wide operations, price response of DERs, DER reserves, etc. (NREL's IGMS)
- Combined distribution powerflow and energy management simulation for next generation tariffs (NREL's IESM)
- Link power hardware-in-the-loop (Opal-RT) to grid-scale time series analysis: GridLab-D, eterraDistribution, etc. (NREL's TEDI)

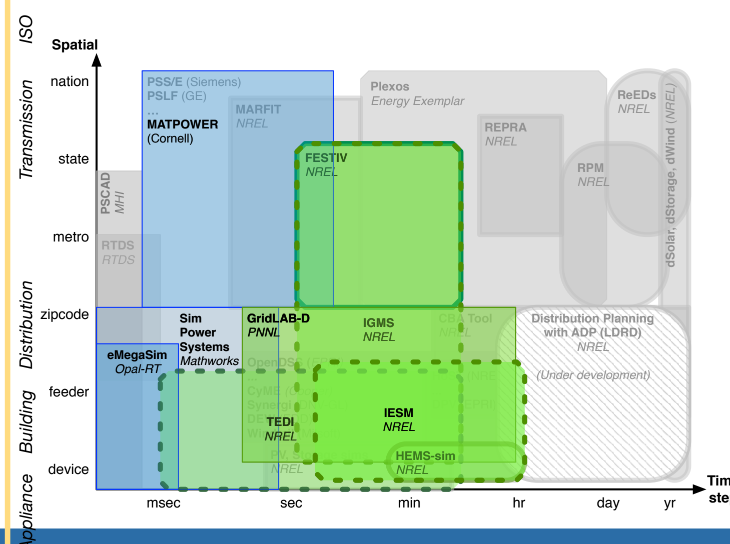
KEY APPLICATION:

Integrated Grid Modeling System (IGMS)

NREL staff worked to develop the unique, modular IGMS framework for integrated market-transmission-distribution-end use co-simulation. Currently: time series simulation of >1M bus T&D systems with rich market, reserve, and load models.







NREL Developed Tool

Integrated T&D Grid Modeling System (IGMS)

Energy Systems Integration

Summary:

A next-generation analysis framework for full-scale transmission & distribution modeling that supports millions of highly distributed energy resources.

End-to-End T&D Modeling Capability

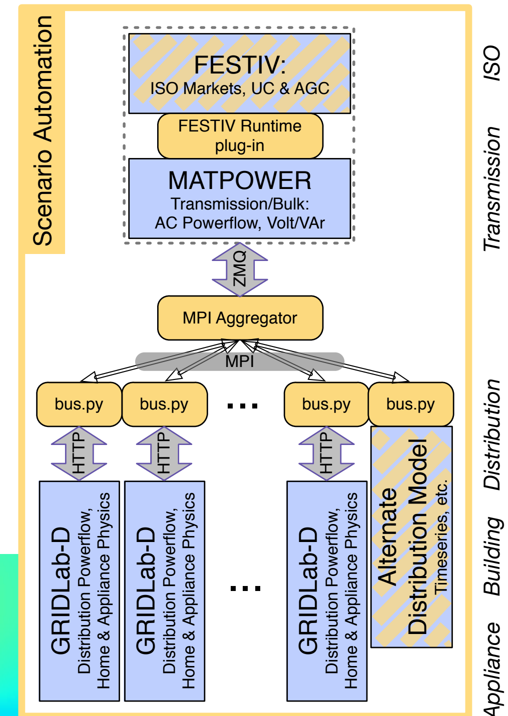
- detailed multi-period wholesale markets (including LMPs)
- generator/reserve dispatch (AGC)
- AC Powerflow (bulk transmission)
- Full unbalanced 3-ph power flow for 100s-1000s of distribution feeders
- Physics based end-use models of buildings and end-use loads.

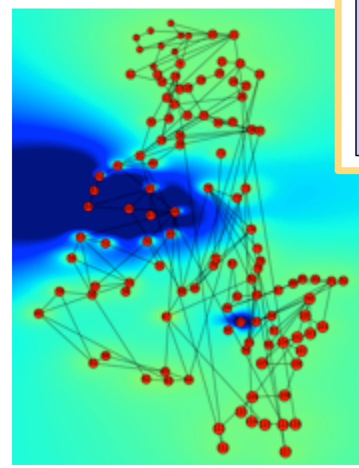
Example Applications

- **Current**: Analyze distributed PV support for grid operations
- **Future:**
  - Simulate smart grid storage, PV, and demand response
  - Simulate alternative market and service architectures
  - Co-simulation with Hardware via PHIL
  - Connect to Advanced DMS/EMS systems

Highlights

- **Successful Medium Scale Run(s): 118 Transmission buses, 743 Distribution Feeders** (PNNL taxonomy)**, >1M total buses, >600k homes**
- **FY15 DoE Solar-SI Reserach:**
  - Automated output processing and visuals
  - Semi-Automated import from PLEXOS, SynerGEE, & CyME
  - Comparison of IGMS to stand-alone tools
- **FY16+ (part of many projects):**
  - Grid Modernization: T+D+C team, other
  - Enhanced Market/Tariff/EMS support





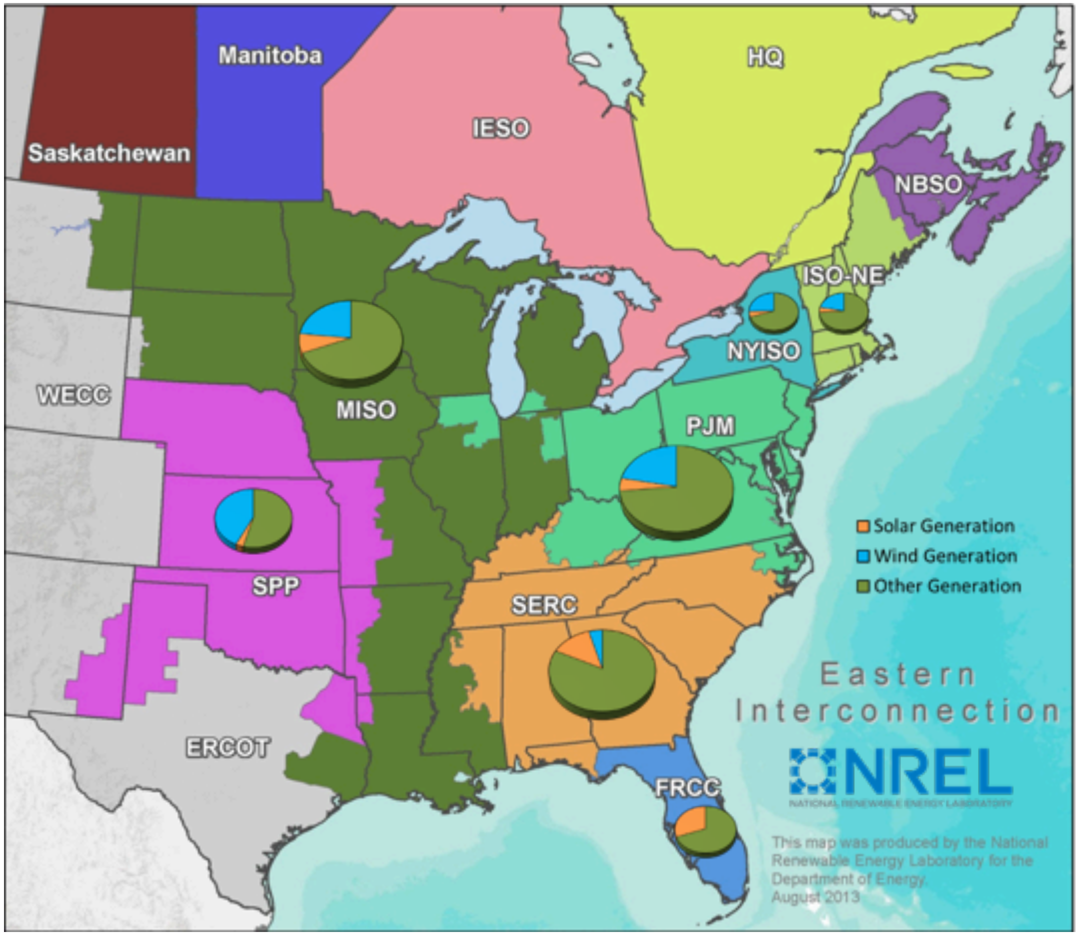
NREL's Integrated Grid Modeling System (IGMS) provides a first-of-a-kind co-simulation with transmission-level markets, 1000s of distribution feeders, and 1Ms of DERs

Eastern Renewable Generation Integration Study

Energy Systems Integration

- **Goals**
  - Operational impact of 30% wind and solar penetration on the Eastern Interconnection at a 5-minute resolution.
  - Efficacy of mitigation options in managing variability and uncertainty in the system.

- **Operational Areas of Interest**
  - Reserves
    - Types
    - Quantities
    - Sharing
  - Commitment and Dispatch
    - Day-ahead
    - 4-hour-ahead
    - Real-time
  - Inter-regional Transactions
    - 1-hour
    - 15-minute
    - 5-minute



This map shows the assumed structure of the Eastern Interconnection in the study year. The pie chart slices indicate the relative amount of solar, wind, and other generation in each region and the relative size of the pies indicates the amount of generation for the Regional 30% RE scenario.

Western Wind and Solar Integration Studies

Energy Systems Integration

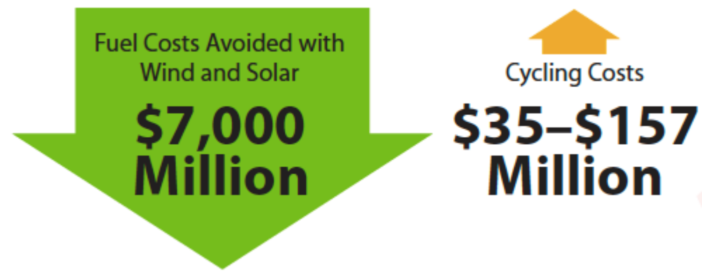
Phase 1: Can WECC handle 35% RE? Yes, with practice change

Phase 2: Cycling Cost and Emissions Impacts

	Emission Reduction Due to Renewables	Cycling Impact
CO_2	260–300 billion lbs, 29%–34%	Negligible Impact
NO_x	170–230 million lbs, 16%–22%	3–4 million lbs
SO_2	80–140 million lbs, 14%–24%	3–4 million lbs

Emissions impacts of cycling are relatively small

From a system perspective, cycling costs are relatively small



Note: Capital costs for wind and solar are not reflected.

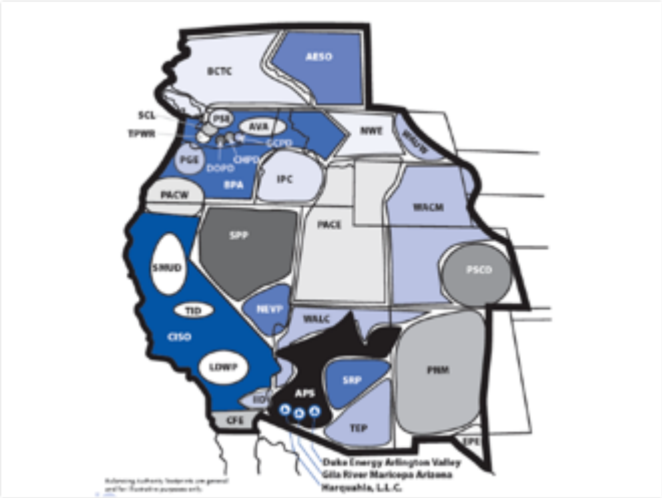
- Phase 3: Frequency Response and Grid Impact

❖ What happens to the transmission grid's frequency with high penetration of distributed generation at low load?

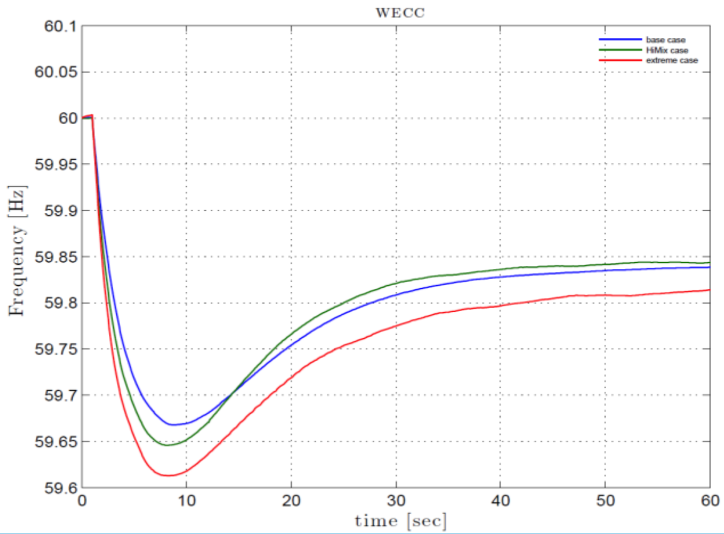
❖ What happens to the grid when remote transmission lines are highly-loaded to move wind long distances?

WWSIS- Phase 3 Key Questions

- **What is the impact of high penetration wind and solar on specific aspects of reliability of the Western Interconnection?**
  - **i.e. "will the system successfully serve customer loads for the first minute after a big disturbance"**
- **What mitigation means are effective in addressing any adverse impact?**



Disturbance: Trip 2 Palo Verde units (~2,750MW)

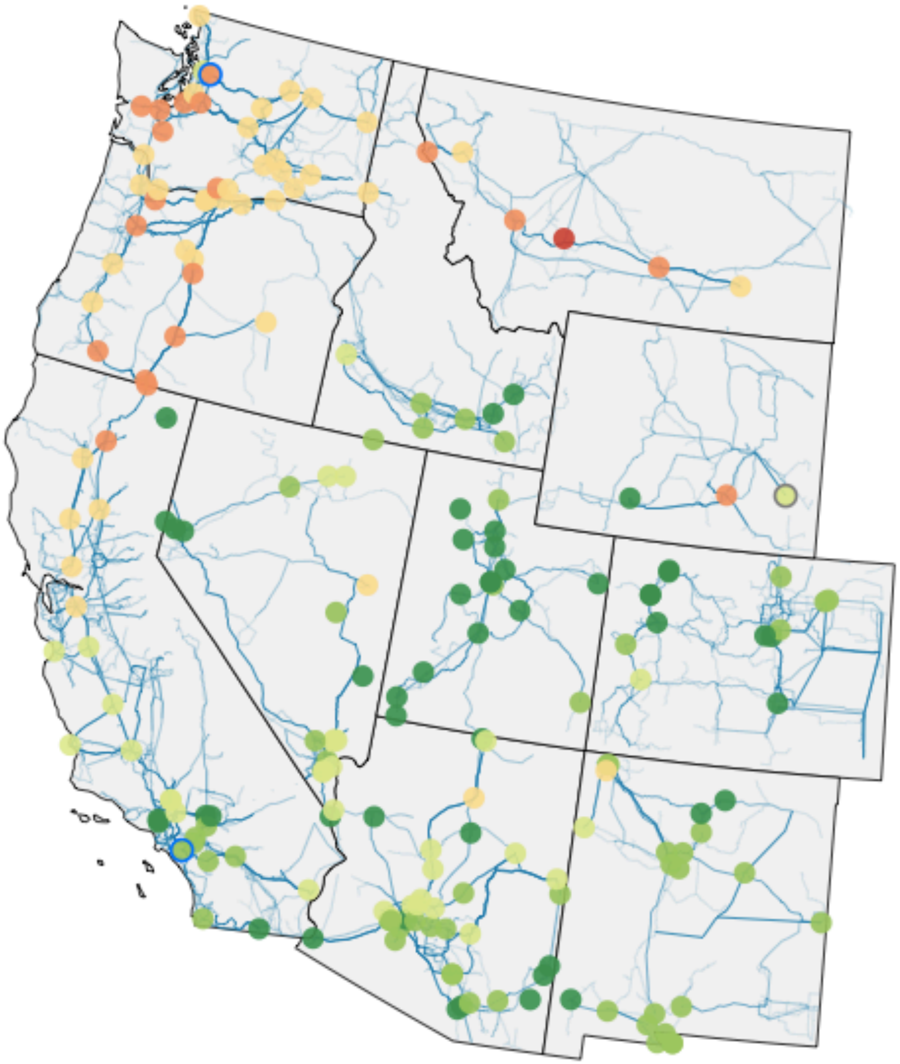


Interconnection frequency response > 840 MW/0.1Hz threshold in all cases.
No under-frequency load shedding (UFLS).

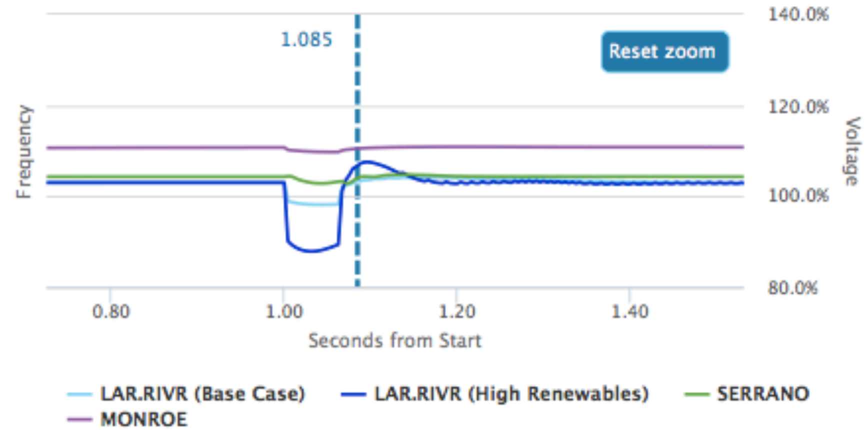
WWSIS 3

Energy Systems Integration

Western Wind and Solar Integration Study



*The primary objectives of Phase 3 of the Western Wind and Solar Integration Study (WWSIS-3) were to examine the large-scale transient stability and frequency response of the Western Interconnection with high wind and solar penetration. WWSIS-3 evaluated a variety of system conditions, disturbances, locations, and renewable penetration levels to help draw broader conclusions. Key finding was that **with good system planning, sound engineering practices, and commercially available technologies, the Western Interconnection can withstand the crucial first minute after grid disturbances with high penetrations of wind and solar.***



Voltage

- 95.0% - 97.5% or 102.5% - 105.0%
- 92.5% - 95.0% or 105.0% - 107.5%
- 90.0% - 92.5% or 107.5% - 110.0%
- 87.5% - 90.0% or 110.0% - 112.5%
- less than 87.5% or more than 112.5%

60.00 **Frequency (Hz)** 60.00

Scenario:

Aeolus Fault High Renewables

0.725 1.533

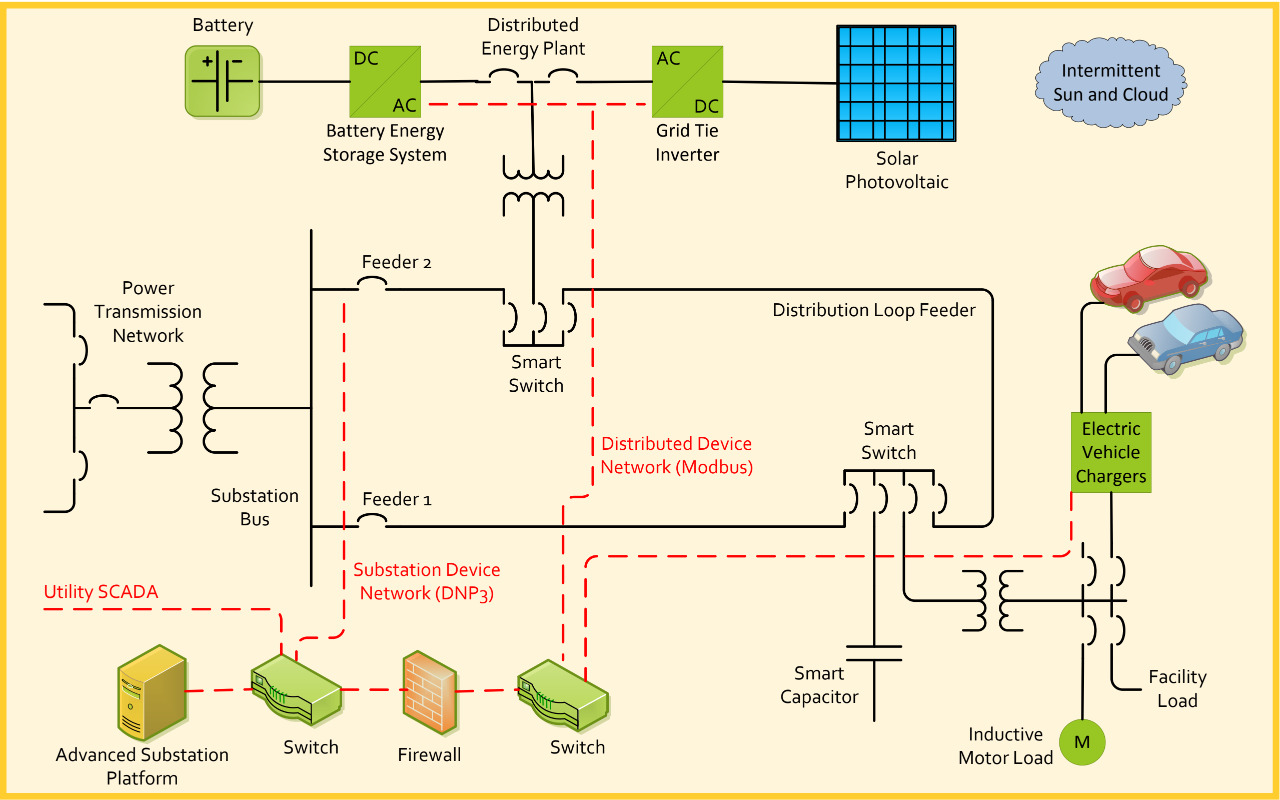
Cybersecurity and Resilience

Energy Systems Integration

- As the number of controllable devices on the grid increases…
- Each node in the IoT network becomes a potential attack surface.
- increasing the potential for large scale compromise of systems initiated from one or more nodes that are in unmanned locations and/or with limited physical security.
- Cybersecurity can be the Achilles Heel of IoT if not addressed properly.

- Need new cyber and physical security controls and resilience best practices that addresses the future grid with milliion of controllable points

Securing Distribution Grid Management (GDM)



Securing Distribution Grid Management (GDM) Use Cases:

- **Volt-VAR management**
- **Auto-Sectionalizing**

- Distill the security requirements from the use cases for the logical layers in the various environments
- Built the distribution system test bed with a DMS, SCADA software, intelligent communication gateway, intelligent electronic devices and actual hardware in ESIF

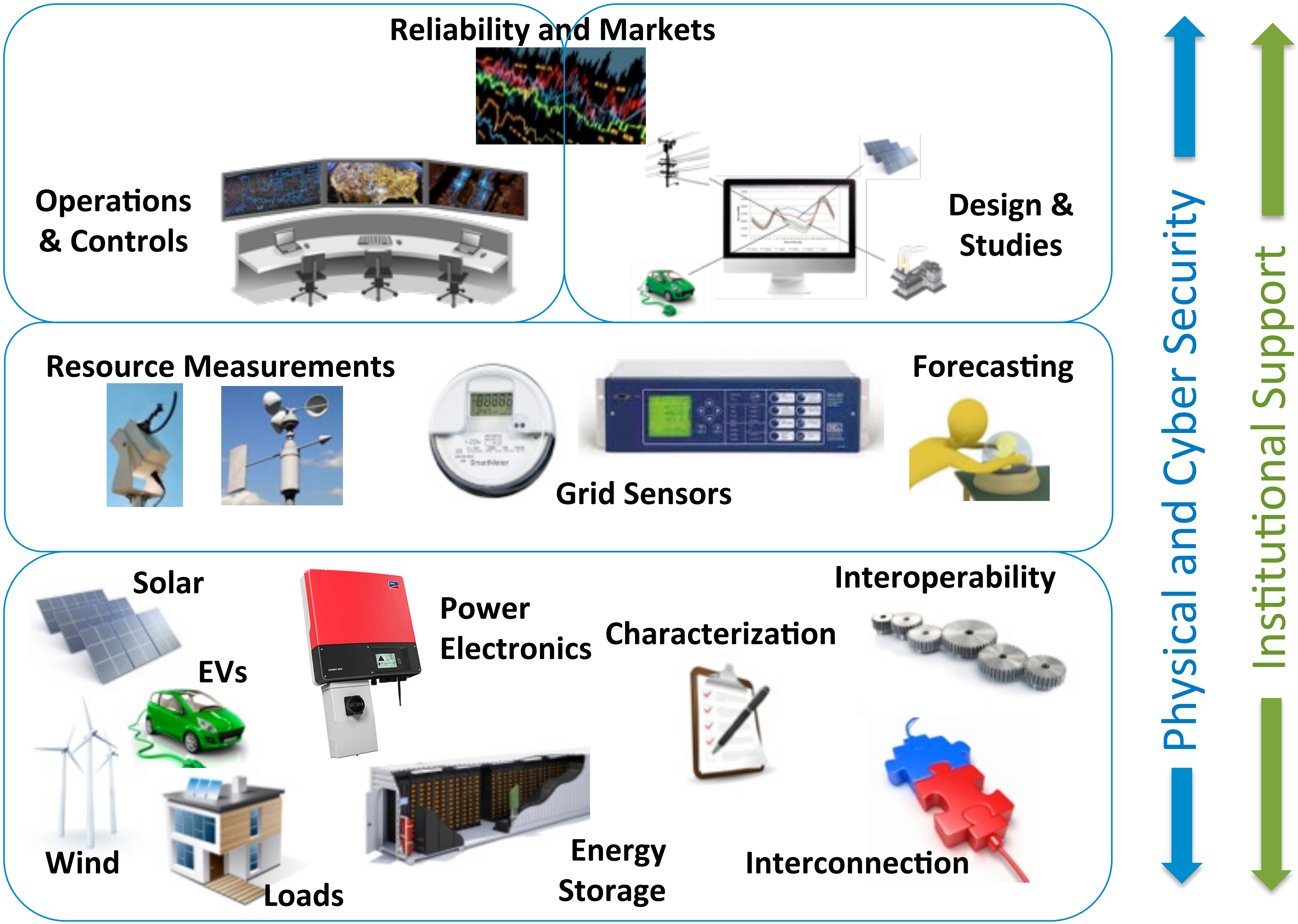
NREL Provides Solutions

Design & Studies

Operations & Controls

Sensing, Measurements, and Forecasting

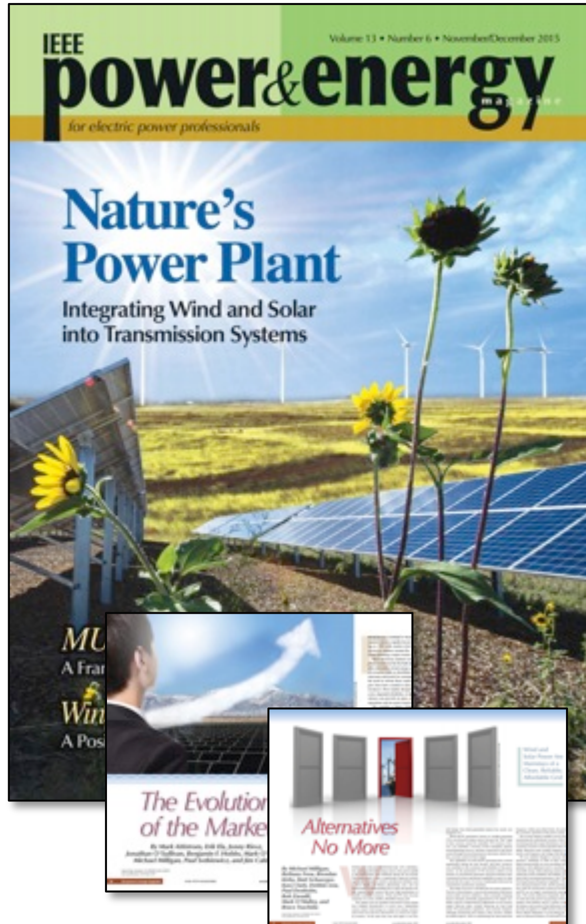
Integrated Devices and Systems



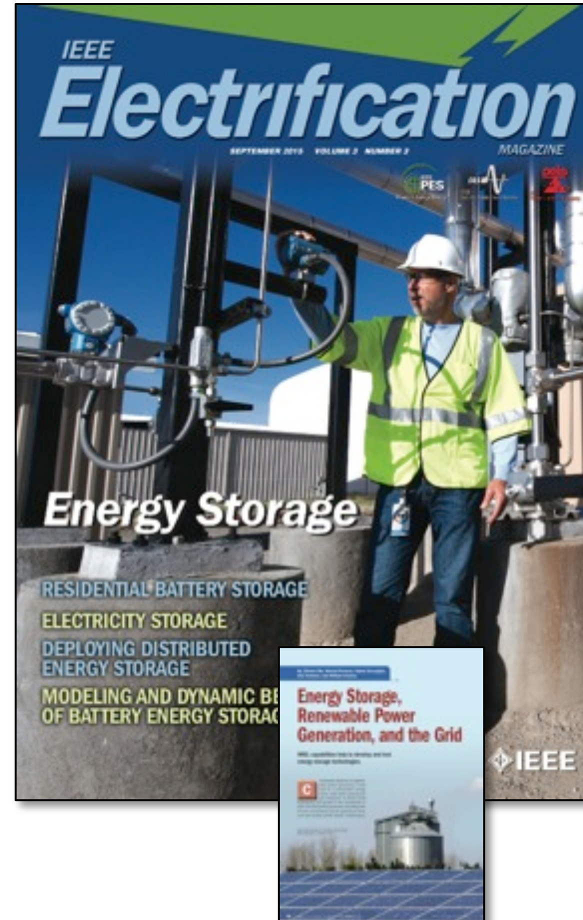
IEEE Industry Journals

Energy Systems Integration

- Mar/Apr 2015 Issue co-edited by Ben Kroposki and Barry Mather
- Articles on Test Labs and SCE PV Integration



- Nov/Dec 2015 Issue co-edited by Barbara O'Neill
- Articles on Markets and Operations



- Sept 2015 Issue edited by Ed Muljadi
- Articles on NREL storage testing capabilities

Thank You

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